PHYSICS OF TECHNOLOGY

COORDINATED BY AMERICAN INSTITUTE OF PHYSICS

ANALYTICAL BALANCE
AUTOMOBILE COLLISIONS
AUTOMOBILE IGNITION SYSTEM
BINOCULARS
CAMERA
CATHODE RAY TUBE
CLOUD CHAMBER
ELECTRIC FAN
FLUORESCENT LAMP
GEIGER COUNTER
GUITAR
HYDRAULIC DEVICES
INCANDESCENT LAMP
LASER
LOUDSPEAKER
MULTIMETER
PHOTODETECTORS
PILE DRIVER
POWER TRANSISTOR
PRESSURE COOKER
SLIDE PROJECTOR
SOLENOID
SPECTROPHOTOMETER
STROBOSCOPE
TOASTER
TORQUE WRENCH
TRANSFORMER

INSTRUCTOR'S MANUAL

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Physics of Technology Series

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In the early days of the Tech Physics Project A. A. Strassenburg, then Director of the AIP Office of Education, coordinated the module quality-control and advisory functions of the National Steering Committee. In 1972 Philip DiLavore became Project Coordinator and also assumed the responsibilities of editing and producing the final page copy for the modules.

The National Steering Committee appointed by the American Institute of Physics has played an important role in the development and review of these modules. Members of this committee are:

Instructor's Manual to Accompany the Physics of Technology Series

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PREFACE

The Physics of Technology program is a 27-module introduction to physics at a pre-calculus level. There is an inherent flexibility in this approach, as 8 to 12 modules would constitute a standard three-hour/two-semester introductory course with laboratory.

The project was originally aimed at students of engineering technology, but the modules are also useful with a broad spectrum of liberal arts students and highly motivational for students of less demanding disciplines.

Each module centers on a common technological device (such as the toaster) and the physical principles upon which it is built. Thus, physics is not presented as a series of isolated and separate concepts. Rather, physics is seen as the dynamic integration of laws which form the basis for our modern technological society.

Each module is inquiry-based. It presents the device in the laboratory in such a way that questions are elicited from the student, who is then guided through a laboratory-oriented exploration to the "discovery" of underlying physical principles.

The Physics of Technology program is easily adapted to various forms of individualized study. Each module is divided into three sections (levels) and includes:

1. A list of mathematics or physics prerequisites where necessary
2. A diagnostic pretest and answers
3. Learning objectives for each section of the module, including examples of questions that the student might be expected to answer upon completion of the module
4. An instructional program with integrated laboratories or demonstrations
5. An instructor's manual including sectional post-tests and equipment demands

The equipment for this project has been kept as simple as possible. While specialized equipment may be obtained from Thornton Associates, the instructor's manual also includes hints on how to make such equipment.

The Physics of Technology project assumes that the student has a familiarity with high school algebra, trigonometric tables, elementary graphing and measuring techniques, scientific notation, areas and volumes of simple geometric shapes, and the Pythagorean Theorem. Specific modular prerequisites are occasionally necessary, and are stated in both the module and the instructor's manual.

Four production centers were involved in the creation of these modules: Florissant Valley Community College, Oak Ridge Associated Universities, the State University of New York at Binghamton, and the Technical Education Research Center at Cambridge. For the past three years, these modules have been tested by these four production centers, and in classes throughout the nation.

E: Development of topic based on laboratory experience
M: Major "theoretical" development of topic
m: Minor treatment of topic

P: Prerequisite topic for module
*: Other modules specified as prerequisite modules

MECHANICS

Module	Speed-Velocity	Uniform acceleration	Non-uniform acceleration	Mass	Forces	Newton's Laws	Mechanical energy	Work-Power	Energy conservation	Momentum-Impulse	Torque	Center of Mass-Gravity	Moment of Inertia	Rotational kinematics-dynamics	Equilibrium	Elasticity-Hooke's law	Levers	Mechanical Advantage	Oscillations-Harmonic Motion	Pressure	Density-Archimedes' law	Pascal's principle	Bernoulli equation
The Analytical Balance				E							E	E			E		E				E		
Automobile Collisions	E	E	E	M	E	M	E		E	E	E	E			E	m							
The Electric Fan	P	P		P	E	P	m				E	E	E	E									
The Pile Driver	E	E		M	m	M	E	E	E	E													
The Stroboscope	E	E	E	m	E	E																	
The Torque Wrench					P						E	m			E	E							
Hydraulic Devices																		E		E	E	E	E
The Guitar					m											M			E				
The Loudspeaker					E																		
The Binoculars*																							
The Camera																							
The Incandescent Lamp																							
The Laser*																							
The Projector																							
The Spectrophotometer																							
The Power Transistor									E														
The Pressure Cooker																				E			
The Toaster									m														
Automobile Ignition System																							
Cathode Ray Tube					E																		
The Multimeter																							
The Solenoid					E						P												
The Transformer*																							
The Cloud Chamber							m																
The Fluorescent Lamp							P	P	P														
The Geiger Counter							P	P	P														
Photodetectors																							

SOUND

Module	Wave properties of sound	Standing waves	Travelling waves	Sound intensity	Sound radiation	Beats	Resonance	Musical Scales
The Analytical Balance								
Automobile Collisions								
The Electric Fan								
The Pile Driver								
The Stroboscope								
The Torque Wrench								
Hydraulic Devices								
The Guitar	E	E	E	E			E	E
The Loudspeaker	E	E	M	E	E	E		
The Binoculars*								
The Camera								
The Incandescent Lamp								
The Laser*								
The Projector								
The Spectrophotometer								
The Power Transistor								
The Pressure Cooker								
The Toaster								
Automobile Ignition System								
Cathode Ray Tube								
The Multimeter								
The Solenoid								
The Transformer*								
The Cloud Chamber								
The Fluorescent Lamp								
The Geiger Counter								
Photodetectors								

OPTICS

Module	Thin lens-Principal rays	Thin Lens- Principal planes	Compound lens	Magnification	Reflection	Refraction	Light as a wave	Light as a particle	Diffraction	Interference	Prisms-Gratings	Spectra	Radiometry-Photometry	Coherence	Temperature scales	Thermometry	Heat transfer
The Analytical Balance																	
Automobile Collisions																	
The Electric Fan																	
The Pile Driver																	
The Stroboscope																	
The Torque Wrench																	
Hydraulic Devices																	
The Guitar																	
The Loudspeaker																	
The Binoculars*		E	E	E	E	E											
The Camera	E		E	E		E											
The Incandescent Lamp							m					E	E		E		
The Laser*							E	E		E				E			
The Projector	E		E	E	E	E											
The Spectrophotometer						M	E		E		E	E	m				
The Power Transistor																E	E
The Pressure Cooker															E	E	
The Toaster															M		
Automobile Ignition System																	
Cathode Ray Tube																	
The Multimeter																	
The Solenoid																	
The Transformer*																	
The Cloud Chamber																	
The Fluorescent Lamp							E				E	E					
The Geiger Counter																	
Photodetectors							m	m				m	E				

THE ANALYTICAL BALANCE

Coverage includes mass and weight, torque, static rotational equilibrium, levers, Archimedes' principle, center of mass, and the relation of empirical laws to physical theories. In addition, some simple error analysis, including the mean and the average deviation, is introduced. The module is designed to be an "entry" module, and thus is suitable for use as the first module encountered by students.

AUTOMOBILE COLLISIONS

Coverage of various topics in kinematics and dynamics, including velocity, acceleration, Newton's laws, conservation of energy, torque,

E: Development of topic based on laboratory experience
M: Major "theoretical" development of topic
m: Minor treatment of topic

P: Prerequisite topic for module
*: Other modules specified as prerequisite modules

THERMODYNAMICS

Module	Thermal equilibrium	Thermal transients	Heat energy	Heat capacity	Latent heat	Thermal expansion	Phase changes	Phase diagrams	Ideal gas law	Energy conversion	First law of thermodynamics	Second law of thermodynamics	Blackbody radiation
The Analytical Balance													
Automobile Collisions													
The Electric Fan													
The Pile Driver													
The Stroboscope													
The Torque Wrench													
Hydraulic Devices													
The Guitar													
The Loudspeaker													
The Binoculars*													
The Camera													
The Incandescent Lamp	E								E				E
The Laser*													
The Projector													
The Spectrophotometer													
The Power Transistor	E	E	m							E			
The Pressure Cooker	E		E	E	E		E	E	E	E			
The Toaster				E		E				E			
Automobile Ignition System													
Cathode Ray Tube													
The Multimeter													
The Solenoid													
The Transformer*										M			
The Cloud Chamber							E						
The Fluorescent Lamp									m				
The Geiger Counter													
Photodetectors													E

ELECTROMAGNETISM

Module	Electric charge	Coulomb's law	Electric field	Voltage-Potential difference	Current-Ohm's law	Joule heating-Power	DC circuits	AC circuits	Capacitance	Inductance	Reactance-Impedance	Magnetic field-Flux	Faraday's law	Ampere's law	Biot-Savart law	Lenz'law	Oscillations	Resonance	Non-linear devices	Semiconductors
The Analytical Balance																				
Automobile Collisions																				
The Electric Fan																				
The Pile Driver																				
The Stroboscope																				
The Torque Wrench																				
Hydraulic Devices																				
The Guitar																				
The Loudspeaker																				
The Binoculars*																				
The Camera																				
The Incandescent Lamp																			E	
The Laser*																				
The Projector																				
The Spectrophotometer																				
The Power Transistor				P	P	P														m
The Pressure Cooker																				
The Toaster					m															
Automobile Ignition System	P	P		P	P		P	E	E	E		E	E		E	E	E			
Cathode Ray Tube	E	E	E	M																
The Multimeter				E	E		E												E	
The Solenoid					P		P					E	E	E	E					
The Transformer*				E	E	E		E	E	E	E	E	E			m	E	E		
The Cloud Chamber																				
The Fluorescent Lamp	P	P		P	P															
The Geiger Counter	P	P		P	P		m													
Photodetectors																				E

MODERN PHYSICS

Module	Emission spectra	Transmission spectra	Absorption spectra	Spectral analysis	Atomic models	Energy levels	Light-matter interaction	Radioactivity	Half-life	Detectors	Ionization
The Analytical Balance											
Automobile Collisions											
The Electric Fan											
The Pile Driver											
The Stroboscope											
The Torque Wrench											
Hydraulic Devices											
The Guitar											
The Loudspeaker											
The Binoculars*											
The Camera											
The Incandescent Lamp	E										
The Laser*					m	m	M				
The Projector											
The Spectrophotometer		E	E	E							
The Power Transistor											
The Pressure Cooker											
The Toaster											
Automobile Ignition System											
Cathode Ray Tube											
The Multimeter											
The Solenoid											
The Transformer*											
The Cloud Chamber								E		E	E
The Fluorescent Lamp	E		E		M	E	E				M
The Geiger Counter					m			E	E	E	
Photodetectors					m		E	M		E	

OTHER

Module	Error analysis	Graphical analysis	Vectors	Special lab techniques
The Analytical Balance	E		m	E
Automobile Collisions				
The Electric Fan		m		E
The Pile Driver		m		
The Stroboscope		M		E
The Torque Wrench		m		
Hydraulic Devices		m		
The Guitar		M		
The Loudspeaker		m		
The Binoculars*		m		
The Camera				
The Incandescent Lamp		m		
The Laser*				E
The Projector		M		
The Spectrophotometer		M		E
The Power Transistor		M		E
The Pressure Cooker		m		E
The Toaster				
Automobile Ignition System				E
Cathode Ray Tube				
The Multimeter				E
The Solenoid				
The Transformer*		M		E
The Cloud Chamber				
The Fluorescent Lamp				
The Geiger Counter	E			E
Photodetectors				E

equilibrium, and conservation of momentum. Although there are no prerequisites, the module is relatively sophisticated. Thus it might be used after one of the other mechanics modules, such as THE ANALYTICAL BALANCE or THE STROBOSCOPE.

AUTOMOBILE IGNITION SYSTEM

Treats a variety of alternating current and magnetic phenomena, including inductance, capacitance, magnetic field, magnetic flux, Faraday's law, Ampere's law, Lenz' law, resonance, and oscillations in AC circuits. Completion of the module also provides a good introduction to the use of the oscilloscope. Prerequisites, which include simple electrostatics and current electricity, can be met by completion of THE CATHODE RAY TUBE and/or THE MULTIMETER.

THE BINOCULARS

Coverage of the geometrical optics of compound lenses (using principal planes), magnification, reflection, and refraction. Knowledge of image formation, focal length, and the thin lens formula are prerequisite. Either THE CAMERA or THE PROJECTOR is a suitable prerequisite module. No special apparatus other than a monocular is required.

THE CAMERA

Covers geometrical optics of thin lenses (with principal ray diagrams), magnification, refraction, and compound lenses. The module has no prerequisites and is suitable for use as an "entry" module. A slightly modified Polaroid camera is the only special apparatus necessary.

THE CATHODE RAY TUBE

Provides an introduction to electrostatics, including charge, Coulomb's law, electric field, current, and electric forces. There are no prerequisites, and the module is suitable for use as an "entry" module.

THE CLOUD CHAMBER

Coverage of phase changes, radioactivity, ionization, and the use of the cloud chamber as a detector of radioactivity. No special apparatus is required, and there are no prerequisites. The module is a two-week introductory module, and it can be used at any convenient point in a course.

THE ELECTRIC FAN

Covers rotational kinematics and dynamics, including rotational speed, rotational acceleration, torque, center of mass, moment of inertia, rotational kinetic energy, and rotational balancing. Knowledge of linear kinematics and Newton's second law is prerequisite. THE PILE DRIVER or THE STROBOSCOPE are suitable preliminary modules. THE ELECTRIC FAN is the only module which treats rotational motion in depth.

THE FLUORESCENT LAMP

Treats some wave properties of light, diffraction gratings, grating spectrometers, emission and absorption spectra, atomic models, energy levels, ionization, and light-matter interactions. Prerequisites are very elementary electrostatics, knowledge of current and voltage, and energy. Although students who have completed other modules in mechanics and electricity should meet the prerequisites, the prerequisites can be covered in a short introductory lecture.

THE GEIGER COUNTER

Coverage of radioactivity, including some properties of radioactive nuclei, half-life, ionization, and the use of a G-M tube as a

detector. Simple analysis of counting errors is also included. Prerequisites are elementary electrostatics, knowledge of current and voltage, and mechanical energy. Although students who have completed other modules in mechanics and electricity should meet the prerequisites, the prerequisites can be covered in a short introductory lecture.

THE GUITAR

Coverage includes mechanical oscillations, Hooke's law, standing and traveling waves, properties of sound waves, sound intensity (decibels and phons), resonance, and musical scales. The module has no prerequisites, and it might be considered as an "entry" module, either into mechanics or possibly into optics.

HYDRAULIC DEVICES

Covers fluid statics and dynamics, including pressure, density, Archimedes' principle, and the Bernoulli equation. Although written at the introductory level, the module might be more rewarding for students if done after at least one other mechanics module.

THE INCANDESCENT LAMP

Treats various topics in applied optics, thermodynamics, and current electricity, including photometry, spectra, Kelvin temperature scale, thermal equilibrium, energy conservation, black body radiation, and the temperature dependence of resistance. The prerequisites, which include simple DC circuits, can be met by working through THE MULTIMETER. This module might be used as a "bridge" from optics to thermodynamics, or to modern physics. Since this is a somewhat sophisticated module, students should have completed several modules before encountering it.

THE LASER

Covers a variety of topics in optics and modern physics, including wave and particle models of light, interference, coherence, atomic models, energy levels, and the interaction between light and matter. Prerequisites are wave motion, mechanical energy, electric charge, voltage, and thermal radiation. Either THE GUITAR or THE LOUDSPEAKER and either THE INCANDESCENT LAMP or THE FLUORESCENT LAMP will provide most of the prerequisites. This is an advanced module which may require more than three weeks of study for some students.

THE LOUDSPEAKER

Treats wave properties of sound, traveling and standing waves, sound intensity, sound radiation, beats, and forces in the loudspeaker. Although the module has no prerequisites, the material on the operation of a loudspeaker might be more easily understood by students who have previously encountered magnetic fields. Either THE LOUDSPEAKER or THE GUITAR will provide adequate coverage of sound.

THE MULTIMETER

Covers DC circuits, including current, voltage, Ohm's law, Kirchoff's laws, and non-ohmic devices. Since there are no prerequisites, the module could serve as an "entry" module. THE MULTIMETER and THE CATHODE RAY TUBE combine to provide a reasonably complete treatment of electrostatics and DC circuits.

PHOTODETECTORS

Coverage of photometry, semiconductors, transmission spectra, crystal (molecular) bonding, light-matter interactions, and the use of various light detectors. Prerequisites are Ohm's law, familiarity with the use of the oscilloscope, and familiarity with exponential functions.

THE PILE DRIVER

Broad coverage of linear kinematics and dynamics, including velocity, acceleration, Newton's laws, work, energy, energy conservation and conversion, momentum, and momentum conservation. The module is suitable as an introductory module, and most of the necessary apparatus is available in typical introductory physics laboratories.

THE POWER TRANSISTOR

Coverage includes heat transfer, conservation and conversion of energy, thermometry (including use of the thermocouple), thermal equilibrium, and thermal transients. Electronic properties of power transistors are not considered. Prerequisites include temperature scales and simple current electricity. The module could be used to complement either THE PRESSURE COOKER or THE TOASTER to provide a broad coverage of thermodynamics.

THE PRESSURE COOKER

Provides broad coverage of thermodynamics, including temperature scales, thermometry (calibration and use of thermistor), pressure, thermal equilibrium, heat, heat capacity, phase changes and diagrams, latent heat, ideal gas law, and energy conversion. No prerequisites are specified, and a thermistor is the only special equipment necessary.

THE SLIDE PROJECTOR

Covers geometrical optics of thin lenses (with principal ray diagrams), magnification, reflection, refraction, and compound lenses. The module, which can be completed in two weeks, is appropriate for use as an "entry" module, and no special equipment is necessary. Either THE SLIDE PROJECTOR or THE CAMERA provides reasonably complete coverage of geometrical optics.

THE SOLENOID

Coverage includes magnetic fields and flux, Faraday's law, Ampere's law, the Biot-Savait law, and magnetic forces. The prerequisites, Ohm's law and simple DC circuits, can be met by completing THE MULTIMETER.

THE SPECTROPHOTOMETER

Covers some aspects of both physical optics and modern physics, including wave properties of light, diffraction, dispersive elements, transmission and absorption spectra, and spectral analysis. The module also provides an introduction to the use of a spectrophotometer. Although there are no prerequisites, the prior completion of another module, such as THE SLIDE PROJECTOR or THE CAMERA, should be considered.

THE STROBOSCOPE

Studies the use of a stroboscope as a tachometer, and linear kinematics and dynamics, including velocity, acceleration, Newton's laws, frictional forces, terminal velocity, and simple harmonic motion. Although the stroboscope is used throughout the module, it is not analyzed in the same sense as other devices are analyzed in other modules. The study of motion through graphical analysis of strobe photographs is familiar to many teachers, and, for this reason, THE STROBOSCOPE may be useful as the first module in a transition from more traditional materials.

THE TOASTER

Covers thermometry, heat energy, heat capacity, phase changes, and conservation of energy. The module has no prerequisites and is suitable for use as an "entry" module.

THE TORQUE WRENCH

Coverage includes torque, center of mass, equilibrium, Hooke's law, and elasticity. Although the idea of force is prerequisite, the module could be used as an "entry" module if the teacher is willing to add the necessary discussion of force. The module provides the most comprehensive treatment of elasticity of any module. The module can be completed in two weeks.

THE TRANSFORMER

Provides coverage of a wide variety of electromagnetic phenomena, including power dissipation in AC circuits, capacitance, inductance, reactance, magnetic fields and flux, reluctance, Faraday's law, Ampere's law, series resonance, hysteresis, and eddy currents. This is an advanced module, and THE MULTIMETER, along with either THE SOLENOID or AUTOMOBILE IGNITION SYSTEM, is prerequisite. Completion of the module provides a good introduction to the oscilloscope.

INSTRUCTOR'S MANUAL FOR THE ANALYTICAL BALANCE

CONTENTS

I INTRODUCTION

The Analytical Balance module has been designed for use in an introductory physics course which has two or three hours of laboratory time per week, and three fifty-minute classes per week. This module is most appropriate as a first module of a two-semester physics course. However, the module can be used at any point in a course, since it has no physics prerequisites.

The module emphasizes: equilibrium, mass and weight, measurement and errors, precision and accuracy, mass density, buoyancy, center of mass, torque, and the relation of empirical laws to physical theories.

The principles treated include the empirical relationship between balance sensitivity and other variables associated with balance, the torque conditions for static equilibrium, the relation of buoyant force to variables associated with a given fluid (Archimedes principle), a theoretical equation for balance sensitivity, the buoyancy correction equation for a balance of random errors in terms of the mean and the average deviation.

II SPECIAL PREREQUISITES

There are no special prerequisites for this module, except that for the Physics of Technology series as a whole: high school algebra.

III TABLE OF CONTENTS OF THE MODULE

IV GOALS

The objectives of the Analytical Balance module have been included at the beginning of each section of the module.

V DISCUSSION OF ACTIVITIES

The module is divided into 3 parts, each representing one week's study.

SECTION A

The first section is largely qualitative. The student is introduced to the balance in the lab, and he makes several observations which raise questions for which answers are not yet provided. The first section is concluded with a verbal discussion of the principles which explain the students' observations, and a summary of the qualitative principles and concepts they have learned.

During this first week, the teacher might also want to do the following:

First Class Period

1. Show the film, "The Modern Balance" (20 minutes).
2. Explain the concept of proportionality, using numerical examples involving sides of similar triangles.
3. Discuss mass and weight with demonstrations. The demonstrations would use an air track (or carts) to arrive at the concept of mass, as discussed in the student text. (The 8mm film loop "Newton's Third Law" and the film "Mass and Weight," 11 minutes, may be used instead of the demonstration.)
4. Discuss Questions 1 and 2.

Experiment A-1. Weights and Balances

The purposes of this experiment are: to familiarize the student with various kinds of balances, including at least two types of analytical balances; to have the student learn first-hand, descriptively, the principles of the balance as a lever; to permit the student to observe the effects of buoyancy due to a fluid on the apparent weight of substances of different densities using a simple balance; to have the student investigate, qualitatively, the relationship between balance sensitivity and the location of the mass of the balance beam system relative to the fulcrum; and to give the student an intuitive grasp of the concept of center of mass.

This experiment is supposed to raise questions about the physics of the balance. Although most of these questions are answered through observations or descriptively in the module, the questions are not yet quantitative. Most of the quantitative and analytical material of the module is based on the qualitative observations students make in this experiment.

Second Class Period

1. Discuss some of the steps and questions of Experiment A-1. Ask about the results students are getting and how these results should be interpreted.
2. Demonstrate the concept of center of mass with various objects.
3. Use subjects to demonstrate stable and unstable equilibrium. Ask questions about the conditions required for stability.
4. Discuss Questions 5 and 6.

Third Class Period

1. Discuss Questions 7, 8, and 9.
2. Discuss those Section A goals and sample items for which students need further explanation.
3. Administer Section A post-test (5 items, 25 minutes).

SECTION B

The second section of the module has the student arrive empirically (in the lab) at the principles of the lever, torque, and center of mass. He also finds an empirical relationship between the sensitivity of a balance and the length of the pan arm and the distance of the center of mass of the beam system below the fulcrum. Concepts of center of mass, torque, conditions for equilibrium, and the empirical equations are discussed quantitatively with appropriate problems and exercises.

Experiment B-1 should be completed

early in the week. If it cannot be done then, this experiment should be done as a demonstration in class. Then Experiment B-2 can be done in the lab. Experiment B-2 should not be done until the material between Experiments B-1 and B-2 has been studied and discussed.

The teacher might want to do the following during this second week of study:

First Class Period

1. Discuss Experiment B-1 in terms of what is to be done and how data are analyzed.
2. Discuss Experiment B-2 in terms of graph preparation and interpretation.
3. If these experiments are too long for the lab time available, all or part of either Experiment B-1 or Experiment B-2 should be done as a demonstration.

Experiment B-1. Principles of the Lever

The purposes of this experiment are: (Part A) for the student to find, empirically, the condition $\underline{M}_1\underline{L}_1 = \underline{M}_2\underline{L}_2$ for horizontal equilibrium; (Part B) for the student to arrive at the empirical relationship $\underline{M}_1\underline{L}_1 = \underline{M}_2\underline{L}_2 + \underline{M}_3\underline{L}_3$, when there are three weights in a balance situation; (Part C) for the student to find that a "third weight" like he observed in Part B can be the mass of the meter stick, provided the concept of center of mass is introduced.

Second Class Period

1. The results of Experiment B-1 (or its demonstration) should be discussed.
2. Discuss Problems 2, 3, 4, 5, 6, and 7.
3. Discuss Questions 10, 11, 12, and 13.

Experiment B-2. Sensitivity of a Balance

The purposes of this experiment are: (Part A) to have the student arrive at the empirical relationship between balance sensitivity and pan arm length; (Part B) to have the student arrive at the empirical relationship between balance sensitivity and distance of the center of mass of the beam system below the fulcrum.

Third Class Period

1. Discuss the concept of balance sensitivity in terms of Problem 8 and Question 14.
2. Discuss the results of Experiment B-2 (ask about Question 15).
3. Discuss those Section B goals and sample test items for which students still need explanation.
4. Administer Section B post-test (5 items, 25 minutes).

SECTION C

Section C is a theoretical and analytical section. It derives the sensitivity equation from the torque condition for static equilibrium and the concept of center of mass. It also introduces buoyancy and deduces Archimedes' principle in a logical argument. The buoyancy correction equation is deduced, and examples and exercises are provided. A discussion of errors leads to a treatment of precision in terms of the mean and average deviation.

The student should do Experiment C-1 early in the week and Experiment C-2 later in the week. If both experiments cannot be done, Experiment C-2 can be demonstrated most easily.

Class time might be devoted to:

First Class Period

1. Ask a sequence of questions to get members of the class to deduce the balance sensitivity equation.
2. Discuss Questions 17, 18, and 19.
3. Demonstrate damped and undamped oscillations using various vibrating or oscillating objects and damping mechanisms.
4. Discuss Questions 20 and 21.

Experiment C-1. Archimedes' Principle

The purposes of this experiment are:

to have the student observe the effects of buoyancy on objects of different densities which are placed in water; to get the student to arrive at Archimedes' principle empirically; and to teach the student the concept of mass density.

Second Class Period

1. Show film "Buoyancy" (14 minutes).
2. Discuss the fulcrum in terms of Problem 11.
3. Do Experiment C-2 as a class demonstration if it cannot be done in the lab.
4. Discuss the results of Experiments C-1 and C-2 if they have been done in the lab.
5. Discuss Question 33 and Problem 16.

Experiment C-2. The Analytical Balance

The purpose of this experiment is to have the student use his understanding of the analytical balance, and of buoyant forces, to make accurate and precise measurements with an analytical balance.

Third Class Period

1. Discuss Problems 17, 18, 19, and 20 and Question 34.
2. Discuss those Section C goals and test items for which students still need explanation.
3. Administer the post-test for Section C (5 items, 25 minutes).

VI SAMPLE DATA

Experiment A-1

Part A

1. (a) Fish scale
   (b) Triple beam balance
   (c) Equal-arm precision balance
   (d) Micro-balance

2.

	First penny (grams)	Second penny (grams)
Weight on A	3	3
Weight on B	3.08	3.14
Weight on C	3.078	3.133
Weight on D	3.0715	3.1390

3.

Balance:	A	B
Difference:	0 g	0.06 g

Balance:	C	D
Difference:	0.065 g	0.0675 g

4. No, some scales or balances read more digits than other scales or balances.

5.

Balance:	A	B
Capacity:	2000 g	311 g

Balance:	C	D
Capacity:	52 g	160 g

6. Set the balance at full capacity, then carefully begin to lower the object onto the pan. If the balance shifts before you have released the weight, it is too heavy for the balance. If the balance does not shift, even when you let go, the object has less mass than the capacity of the balance.

7.

Balance:	A	B
Weight of First Object:	70 g	69.79 g
Weight of Second Object:	70	69.89
Difference:	0	0.10

Balance:	C	D
Weight of First Object:	-	69.742 g
Weight of Second Object:	-	69.865
Difference:	-	0.123

8. No, and the pattern is the same as previously observed.

Part B
1. 50.1 cm.
2. The right side of the lever moved down.
3. The same amount as had been put on the right side.
4. The left side of the lever system moved down. Weights were added to the right side.
5. The further the fulcrum is moved to the right, the more weight must be added to that side.

Part C
1. The right side of the lever goes down, as if the left side had lost weight. The water level rises. Some of the weight was taken off the right. I removed 33 grams from the right side to achieve balance.
   When weights are immersed in water, there is a buoyancy effect, causing the left side to weigh less.
2. The right side of the lever system goes down. The water level rises more than before. To get balance, remove some of the weights on the right side.
   More weights had to be removed than before. With the glass beads, there is more volume than before, so volume has something to do with buoyancy.

Part D
1. When 10 g was placed on the weight holder, that side went down and came to rest.
2. With the movable weight higher, a small weight caused the side to go down much further before coming to rest.
3. The meter stick goes over and falls off the support.
4. There is no part of the weight below the fulcrum.

Part E
1. The cardboard balances on the tip of your finger.
2. The point formed on the cardboard is some kind of center of balance. The center of the meter stick is also a center of balance.

Experiment B-1
Part A
1. Position of fulcrum = 50.2 cm.
2. Mass of left pan support = 24.6 g.
   Mass of right pan support = 25.1 g.
   Mass of left weight holder = 49.9 g.
   Mass of right weight holder = 49.9 g.

3.

Trial:	1	2
L_2 (cm):	20.0	15.0

Trial:	3	4
L_2 (cm):	10.0	30.0

4. As M_2 increases, L_2 decreases. L_2 is one-half L_1. L_2 is twice L_1.
5. $M_1L_1 = M_2L_2$.

Part B
1. Mass of third pan support = 25.0 g.
   Mass of third weight holder = 49.9 g.

2.

Trial:	1	2
L_3 (cm):	19.9	19.9

Trial:	3	4
L_3 (cm)	10.0	14.9

3.

Trial	M_1L_1 (g-cm)	M_2L_2 (g-cm)	M_3L_3 (g-cm)
1	8000	6000	1990
2	6400	4000	2388
3	4500	3000	1500
4	6000	3000	2980

4. $M_1L_1 = M_2L_2 + M_3L_3$.

Part C
1. Position of fulcrum = 40.2 cm.

2. Trial: 1 2

L_2 (cm): 31.1 8.9

Trial: 3 4

L_2 (cm): 15.5 11.6

3. M_1L_1 is, in each trial, larger than M_2L_2 by an average of 1339 g-cm.
4. Weight of meter stick = 131.9 g.
5. This product, 1319 g-cm, is nearly the same as the constant difference found in Step 3.
6. All the mass of the meter stick must be considered as being at 50.2 cm, the position where it balances.

5. L_p (cm): 15 25

E (div/mg): .00052 .00075

L_p (cm): 35 45

E (div/mag): .00106 .00131

6. See graph on next page.

Experiment B-2

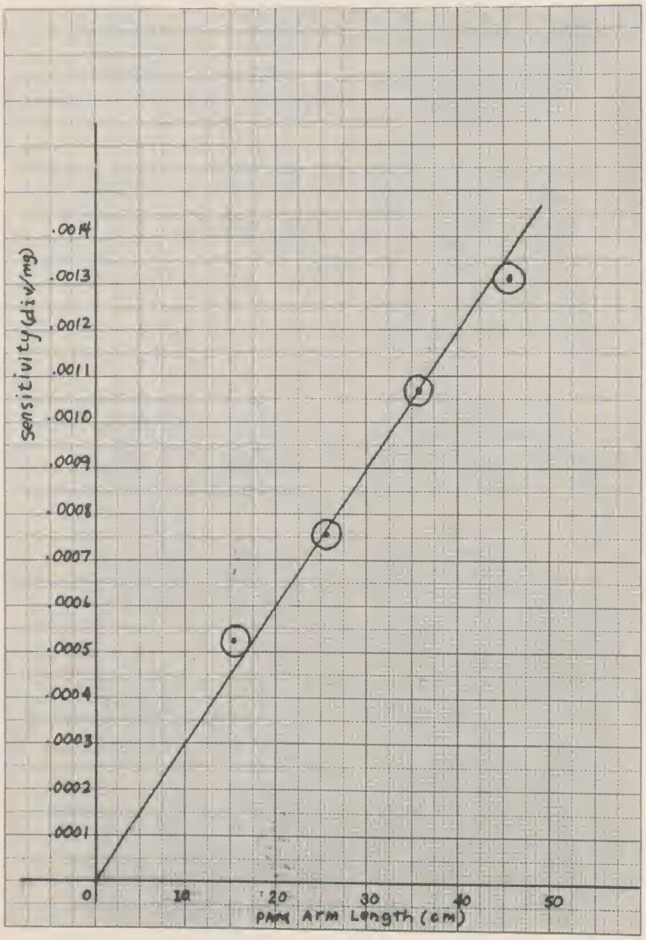
Part A

1. Position of fulcrum = 50.2 cm.
2. Mass of beam system = 271.5 g.
3. Length of pointer (from fulcrum to pointer tip) = 23.3 cm.
   Load on each side of fulcrum = 150 grams

Trial	Additional mass, m_o, in grams	Deflection s produced by m_o (pan arm = 15 cm)	Deflection s produced by m_o (pan arm = 25 cm)	Deflection s produced by m_o (pan arm = 35 cm)	Deflection s produced by m_o (pan arm = 45 cm)
1	2	1-1/4	1-1/2	2-1/2	3
2	4	2-1/4	3-1/4	4-1/4	5-1/4
3	6	3	4-1/2	6	7-1/2
4	8	3-3/4	5-3/4	8	10
5	10	4-1/2	7-1/4	9-3/4	12-1/4

4.

Trial	Additional mass, m_o, in grams	Sensitivity (pan arm = 15 cm)	Sensitivity (pan arm = 25 cm)	Sensitivity (pan arm = 35 cm)	Sensitivity (pan arm = 45 cm)
1	2	0.62	0.75	1.25	1.50
2	4	0.56	0.81	1.06	1.31
3	6	0.50	0.75	1.00	1.25
4	8	0.47	0.72	1.00	1.25
5	10	0.45	0.72	0.98	1.22
Total		2.60	3.75	5.29	6.53
Average		0.52	0.75	1.06	1.31



7. The sensitivity is directly proportional to the pan arm length
8. $\underline{E} = (3.0 \times 10^{-5})\underline{L}_p$, when $\underline{E}$ is in div/mg and $\underline{L}_p$ is in cm.

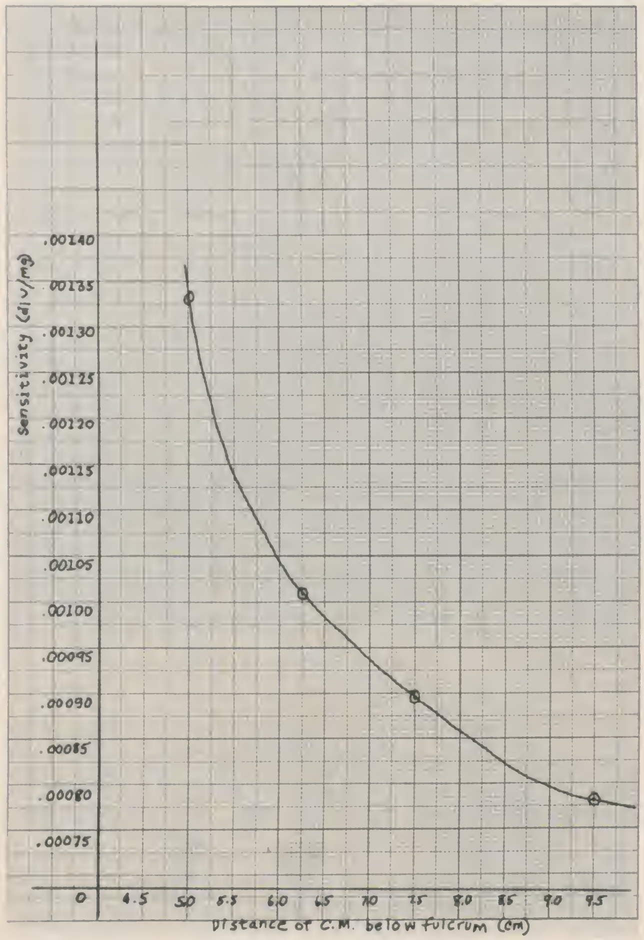
Part B

1. $\underline{M}$ = 271.5 g.
2. $\underline{M}_{beam} = 2\underline{M}$ = 543 g.
3. $2\underline{d}$ = 10.0 cm.
   $\underline{d}$ = 5.0 cm.
4. $\underline{E}$ = .00134 div/mg.
5. $\underline{d}$ = 6.25 cm; $\underline{E}$ = .00102 div/mg.
6. $\underline{d}$ = 7.5 cm; $\underline{E}$ = .00091 div/mg.
   $\underline{d}$ = 9.5 cm; $\underline{E}$ = .00080 div/mg.

7.

$\underline{d}$ (cm):	5.0	6.25
$\underline{E}$ (div/mg):	.00134	.00102
$\underline{d}$ (cm):	7.5	9.5
$\underline{E}$ (div/mg):	.00091	.00080

See graph below.

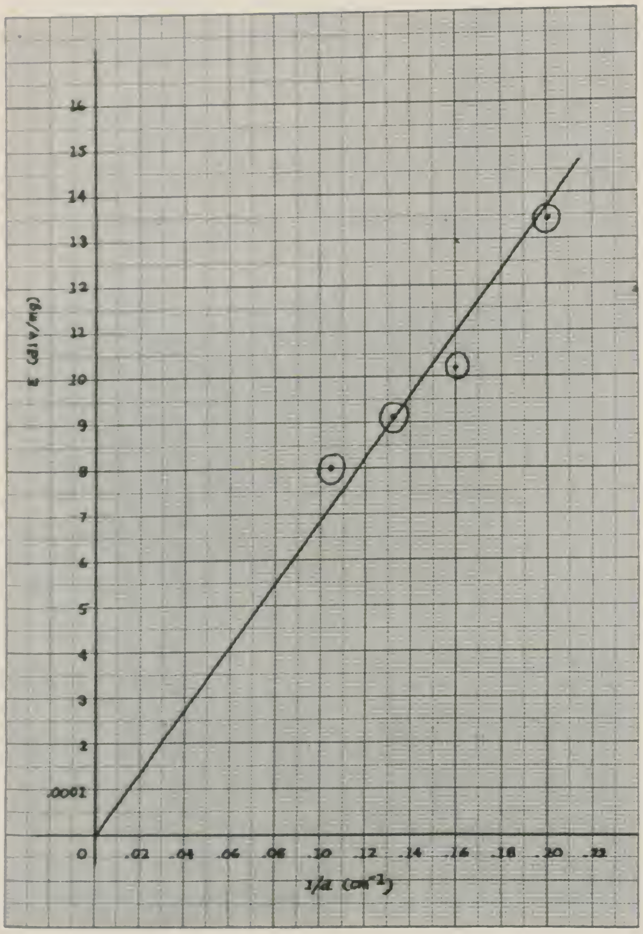


8. As the distance increases, the sensitivity decreases.

9.

$\underline{E}$ (div/mg):	.00134	.00102
$1/\underline{d}$:	0.200	0.160
$\underline{E}$ (div/mg):	.00091	.00080
$1/\underline{d}$:	0.133	0.105

See graph on next page.



10. $E = 6.7 \times 10^{-3}(1/d)$, where E is in div/mg and d is in cm.

Experiment C-1

1, 2.

	(1) Al	(2) Zn	(3) Sn
L (cm)	8.50	8.40	3.30
d (cm)	1.85	1.85	1.85
V (cm^3)	22.8	9.13	8.86

	(4) Cu	(5) Pb
L (cm)	2.70	2.10
d (cm)	1.85	1.85
V (cm^3)	7.25	5.64

3, 4.

	1	2	3
M_a (g)	69.8	69.8	70.0
M_w (g)	46.0	60.0	60.4

	4	5
M_a (g)	70.0	70.1
M_w (g)	62.1	63.9

5. M = 97.8 g.
ρ = 0.98 g/cm^3.

6.

	1	2	3
$\rho_w V_w$ (g)	24.2	9.3	9.3
$M_a - M_w$	23.8	9.8	9.6

	4	5
$\rho_w V_w$ (g)	7.8	6.4
$M_a - M_w$	7.9	6.2

The weight of water displaced is, in each case, nearly the same as the upward buoyant force.

Experiment C-2

1. Correction for glass = 3.1×10^{-4}
Correction for lead = 4.3×10^{-5}
2. M_s = 2.4300 g (M_w = 2.4292 g).
3. M_s = 70.0896 g (M_w = 70.0926 g).
4.

Penny:	1	2
Uncorrected mass (g):	3.0887	3.0344

Penny:	3	4
Uncorrected mass (g):	3.1667	2.9566

Penny:	5	6
Uncorrected mass (g):	3.1133	3.1722

Penny:	7	8
Uncorrected mass (g):	3.0684	3.1096

Penny:	9	10
Uncorrected mass (g):	3.1084	8.0867

The buoyancy correction does not affect these measurements, even in the fourth decimal place.

VII SOLUTION TO PROBLEMS

The problems and questions of this module are an important part of the module and should be discussed in class if possible.

1. Cart 1 has a larger mass. The mass of Cart 1 is four times larger than the mass of Cart 2. If the mass of Cart 2 is 1 unit, then the mass of Cart 1 must be 4 units.
2. Can be verified by student.
3. 80 lb.
4. 0.294 newton-meters.
5. Given $M_1L_1 = M_2L_2 + M_3L_3$, multiply both sides by g, so that

   $$(M_1g)L_1 = (M_2g)L_2 + (M_3g)L_3.$$

   Then, using the relationship $W = Mg$

   $$W_1L_1 = W_2L_2 + W_3L_3$$

6. 20 cm.
7. 21.4 lb.
8. 0.1 div/mg; 1 div = 10 mg.
9. D = 23.3 cm and 1 scale division = 1/8 inch. Therefore (since 2.54 cm = 1 inch), D = 73.4 div. We then have, as a theoretical equation,

   $$E = (2.73 \times 10^{-5})L_p$$

   Typical student data gives an empirical graph having the equation

   $$E = (3.0 \times 10^{-5})L_p$$

   where in each case, L_p is in cm and E is in div/mg.
10. The theoretical equation is

    $$E = 6.1 \times 10^{-3}(1/d)$$

    and the empirical graph has the equation

    $$E = 6.7 \times 10^{-3}(1/d)$$

    where d is in cm and E is in div/mg.
11. 3,300 lb/in^2.
12. 3 g/cm^3.
13. 8.4 x 10^4 g. Yes, this balloon will lift a 170-lb man.
14. 13 g/cm^3; larger.
15. 106.8676 g.
16. 2.1078 g.
17. 3.0953 g.
18. 0.0370 g; 0.0622 g.
19. Deviations: .0222; .0144; .0065; .0282; .0200; .0063; .0127; .0205; .0154; .0075. Average deviation = 0.154 g.
20. Case II. Highest value = 2.59; average value = 2.57; lowest value = 2.55.
    Using average deviation, range = 2.57 ± 0.01.
    As a percentage, range = 2.57 ± 0.4%.
    Case III. Highest value = 2.58; average value = 2.47; lowest value = 2.38.
    Using average deviation, range = 2.47 ± 0.07.
    As a percentage, range = 2.47 ± 2.8%.

VIII POST-TESTS

Test A-1

1. The module contains a description of

a demonstration that may be done using two low-friction carts connected by a compressed spring and a string fastened to each cart. When the string was cut the carts moved apart at a constant speed. How are the distances that the two carts move in a given time related to their speeds? How do you arrive at this relationship?

2. The mass of one object is 2 mass units. At a certain place, its weight is 10 weight units. Another object has a mass of 5 units. What is its weight?
3. Suppose that you have a first class lever made of a very light-weight material (much less weight than that of the masses supported at the ends of the lever). Initially, the lever is in horizontal equilibrium, with the same masses on each end and with the same distance from the fulcrum to each weight support. If the right weight holder is moved closer to the fulcrum, which way must the fulcrum be moved to keep the system in horizontal equilibrium? Explain why the fulcrum must move in this direction.
4. The following are descriptions of three lever systems, designated I, II, and III.
   I. A see-saw pivoted in the middle has two children of equal mass seated on each end.
   II. A steel I-beam is lifted at a construction site by a crane with a single flexible cable that makes a single loop around the center of the I-beam. The beam starts to tilt as it is lifted.
   III. A pencil balanced on a finger starts to tilt in one direction.

   Which systems are in stable equilibrium, and which are in unstable equilibrium? Explain why each situation is as you describe it.
5. A first class lever used as a balance has an iron object on the left pan. The system is in horizontal equilibrium in air. Then a lead (a much "heavier" substance than iron) object is used to replace the iron weight on the left pan. Again the system is found to be in horizontal equilibrium. Even though the buoyant force difference was not observed in this instance, how does the buoyant force due to air on the lead object compare with that on the iron object?

Test A-2

1. The module contains a description of a demonstration that may be done using two low-friction carts connected by a compressed spring and a string fastened to each cart. When the string was cut the carts moved apart at a constant speed. Suppose that two such carts are connected and that the ratio of the mass of cart 2 to that of cart 1 is 2. At a certain time after the string is cut, what will be the ratio of distance 2 to distance 1?
2. If two objects have the same mass, is there any way in which the two may have different weights? Give the reason for your answer.
3. Suppose that you have a first class lever made of a very light-weight material (much less weight than that of the masses supported at the ends of the lever). Initially, the lever is in horizontal equilibrium, with the same masses on each end and with the same distance from the fulcrum to each weight support. If the left weight holder is moved farther from the fulcrum, which way must the fulcrum be moved to keep the system in horizontal equilibrium? Explain why the fulcrum must move in this direction.
4. A set of "weight lifting" weights consists of a light rod connecting identical heavy discs on both ends of the rod. The center of mass of this system lies inside the rod and halfway between the ends of the rod. Describe the effect on the center of mass of this system if one more disc

is added to the right side than is on the left.

5. A first class lever used as a balance has an iron object on the left pan. The system is in horizontal equilibrium in air. Then a wood (a much "lighter" substance than iron) object is used to replace the iron weight on the left pan. Again the system is found to be in horizontal equilibrium. Even though the buoyant force difference was not observed in this instance, how does the buoyant force due to air on the wood object compare with that on the iron object?

Test B-1

1. A first class lever is in horizontal equilibrium. An object having a mass of 50 g is added to a weight holder which is 15 cm to the right of the fulcrum (as you face the lever system). What is the value of the resulting torque, and what effect does the torque have on the lever system?
2. A lever system has several weights suspended at different points on each side of the fulcrum. Suppose that the torques due to weights on the right of the fulcrum (as you face the lever system) are: 1.20 N·m; 0.50 N·m; 0.60 N·m. Suppose that the torques due to weights on the left of the fulcrum are: 0.70 N·m; 0.30 N·m; 0.90 N·m; 0.40 N·m. What is the sum of the clockwise torques? What is the net torque, and what effect will it have on the system? Show how you make these calculations.
3. Two girls, one with a mass of 35 kg and the other with a mass of 20 kg, attempt to balance themselves horizontally on a see-saw which is 3 meters long and has a mass of 30 kg. Each girl is seated 1/2 meter from her end, and they have placed the see-saw so that its fulcrum is 1/2 meter from the center toward the 35-kg girl. Taking all masses into account, what is the torque about the fulcrum due to the weight of this system? Show how you arrive at this result.
4. The smallest division that can be read on a particular analytical balance is marked as 0.1 mg. What is the sensitivity of this balance? What is the reciprocal sensitivity? Show the definitions which you used to get your answers.
5. Suppose that in the experiment in the module on sensitivity, using the meter stick balance with the fulcrum at the center, you obtained a sensitivity of 1.5 div/g when the distance from the pan support to the fulcrum was 25 cm. When this distance was increased to 45 cm, what would the sensitivity of the balance have been? Explain or show how you arrive at your answer.

Test B-2

1. A first class lever is in horizontal equilibrium. An object having a mass of 30 g is added to a weight holder which is 20 cm to the left of the fulcrum (as you face the lever system). What is the value of the resulting torque, and what effect does the torque have on the lever system?
2. A lever system has several weights suspended at different points on each side of the fulcrum. Suppose that the torque due to weights on the right of the fulcrum (as you face the lever system) are: 1.00 N·m; 0.70 N·m; 0.60 N·m; 0.20 N·m. Suppose that the torques due to weights on the left of the fulcrum are 0.50 N·m; 0.90 N·m; 0.60 N·m. What is the sum of the clockwise torques? What is the net torque, and what effect will it have on the system? Show how you make these calculations.
3. Two girls, one with a mass of 40 kg and the other with a mass of 15 kg, attempt to balance themselves horizontally on a see-saw which is 4 meters long and has a mass of 40 kg. Each girl is seated 1/2 meter

from her end, and they have placed the see-saw so that its fulcrum is 1/2 meter from the center toward the 40 kg girl. Taking all masses into account, what is the torque about the fulcrum due to the weight of this system? Show how you arrive at this result.

4. The smallest division that can be read on a particular analytical balance is marked as 0.5 mg. What is the sensitivity of this balance? What is the reciprocal sensitivity? Show the definitions which you used to get your answers.
5. Suppose that in the experiment in the module on sensitivity using the meter stick balance with the fulcrum at the center, you obtained a sensitivity of 0.75 div/g when the distance from the pan support to the fulcrum was 25 cm. When this distance was decreased to 15 cm, what would the sensitivity of the balance have been? Explain or show how you arrive at your answer.

Test C-1

1. The densities of different kinds of woods vary so much that the least dense float in water with very little of their volume below the surface, and the most dense will sink in water. A sample of ebony is twice as dense as a sample of walnut, which is twice as dense as a sample of bamboo. Showing all work, or giving explanations, answer the following questions:
   a. Suppose you have a sample of ebony and a sample of bamboo, each with the same mass. How would the volume of the ebony compare with the volume of the bamboo?
   b. Suppose you have two equal-mass samples, one of walnut and one of bamboo. How would the volume of bamboo compare with the volume of walnut?
   c. Suppose you have two samples with the same volume, one of walnut and the other of ebony. How would the mass of the walnut sample compare with the mass of the ebony?
   d. Suppose you have two samples of walnut, one with twice the volume of the other. How would the masses of the two samples compare?
2. The buoyancy correction equation is given by:

$$\underline{M_s} = \underline{M_w}\left[1 + \underline{\rho_a}\left(\frac{1}{\underline{\rho_s}} - \frac{1}{\underline{\rho_w}}\right)\right]$$

   A single pan analytical balance is used to weight a sample of lead. The standard masses of the balance are made of stainless steel having a density of 8.02 g/cm^3, and lead has a density of 11.3 g/cm^3. If the balance reading is 28.6935 g, what is the mass, corrected for buoyancy? $\underline{\rho_a} = 1.2 \times 10^{-3}$ g/cm^3. Show each step in your calculation.
3. What is the value of the arithmetic mean for the following measurements of the mass of a sample?

Trial	Measurement
1	0.751 g
2	0.747 g
3	0.750 g
4	0.748 g
5	0.748 g
6	0.750 g

4. Two sets of mass measurements are made on the same object, one set using Balance A, the other set using Balance B. For Balance A, the mean is 9.89 g and the mean deviation is 0.02 g. For Balance B, the mean is 9.76 g and the mean deviation is 0.08 g. What is the "best value" of each set of measurements? Do these "best values" differ from each other significantly? Why or why not?
5. A balance has a sensitivity of 3.0 div/mg. To improve the sensitivity, the distance of the center of mass of the beam system below the fulcrum

is decreased. The new distance for the center of mass is one-half the former distance. Also the mass of the beam is 1-1/2 times the former mass. What is the final sensitivity of this balance? Show how you arrive at your answer.

Test C-2

1. The densities of rocks and minerals vary over a wide range. A sample of iron ore (hematite) has a density of 5 g/cm^3; a sample of alabaster, a density of 2.5 g/cm^3; and a sample of mica, 3.0 g/cm^3. Showing all work, or giving explanations, answer the following questions:
   (a) Suppose the sample of iron ore and the sample of alabaster have the same mass. How would the volume of iron ore compare with the volume of alabaster?
   (b) Suppose you have two equal mass samples, one of alabaster and one of mica. How would the volume of alabaster compare with the volume of mica?
   (c) Suppose you have two samples with the same volume, one of iron ore and one of mica. How would the mass of iron ore compare with the mass of mica?
   (d) Suppose you have two samples of iron ore, one with twice the volume of the other. How would the masses of the two samples compare?
2. The buoyancy correction equation is given by:

$$M_s = M_w \left[1 + \rho_a \left(\frac{1}{\rho_s} - \frac{1}{\rho_w} \right) \right]$$

A single pan analytical balance is used to weigh a large diamond. The standard masses of the balance are made of stainless steel having a density of 8.02 g/cm^3, and the diamond has a density of 3.25 g/cm^3. If the balance reading is 3.4225 g, what is the mass corrected for buoyancy? $\rho_a = 1.2 \times 10^{-3}$ g/cm^3. Show each step in your calculation.
3. What is the value of the arithmetic mean for the following measurements of the length of a sample?

Trial	Measurement
1	20.375 cm
2	20.370 cm
3	20.395 cm
4	20.380 cm
5	20.375 cm
6	20.385 cm

4. Two sets of mass measurements are made on the same object, one set using Balance A, the other set using Balance B. For Balance A, the mean is 17.54 g and the mean deviation is 0.03 g. For Balance B, the mean is 17.46 g and the mean deviation is 0.07 g. What is the "best value" of each set of measurements? Do these "best values" differ from each other significantly? Why or why not?
5. A balance has a sensitivity of 2.0 div/mg. To improve the sensitivity, the distance of the center of mass of the beam system below the fulcrum is decreased. The new distance for the center of mass is 2/3 of the former distance. Also, the mass of the beam is 1-1/3 times the former mass. What is the final sensitivity of this balance? Show how you arrive at your answer.

ANSWERS TO POST-TESTS

Test A-1

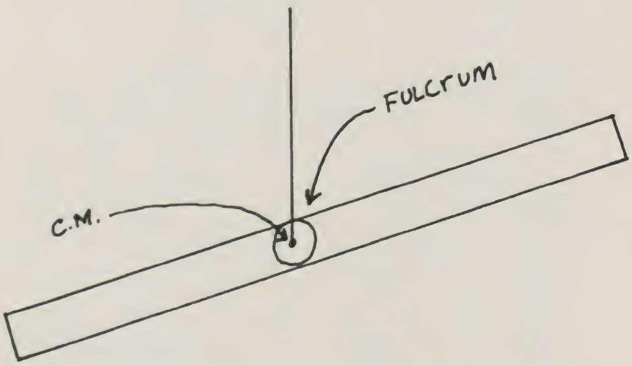
1. $\left.\begin{aligned} d_1 &= v_1 t \\ d_2 &= v_2 t \end{aligned}\right\} \Rightarrow \dfrac{d_1}{d_2} = \dfrac{v_1 t}{v_2 t} = \dfrac{v_1}{v_2}$

   Thus, $d_1/d_2 = v_1/v_2$.

2. $\dfrac{w_1}{m_1} = \dfrac{w_2}{m_2}$ $\qquad \dfrac{10}{2} = \dfrac{w_2}{5}$

   $w_2 = 25$ weight units

3. The fulcrum must be moved to the left. Then the turning effect on the left will again be the same as that on the right.
4. Case I is unstable because the mass of the system is above the fulcrum.
   Case II is stable because the mass of the I-beam is below the fulcrum (as shown below).



   Case III is unstable because the mass of the pencil is above the fulcrum.
5. The buoyant force on the lead is less than the buoyant force on the iron object because iron of about the same weight as a sample of lead occupies more volume than the lead.

Test A-2

1. $\frac{d_2}{d_1} = \frac{m_1}{m_2}$ $\frac{d_2}{d_1} = \frac{1}{2}$
2. Yes, they may be weighed in different places, such as on the earth and on the moon, where the proportionality constants between weight and mass are different.
3. The fulcrum must be moved to the left. Then the turning effect on the left will again be the same as that on the right.
4. The center of mass will move toward the right side along the center of the rod.
5. The buoyant force on the wood object is more than the buoyant force on the iron object because iron of about the same weight as a sample of wood occupies less volume than the wood.

Test B-1

1. Torque = $Mg\ell$ = (0.050 kg) (9.8 m/s^2) (0.15 m) = 0.0735 N·m. The torque will tend to rotate the system clockwise.
2. Clockwise torque = 2.30 N·m. Counterclockwise torque = 2.30 N·m. Net torque = 0. The system will be in equilibrium.
3. One direction: (20)(9.8) (1.5) + (30) (9.8) (6.5) = 441 N·m.
   Other direction: (35) (9.8) (0.5) = 172 N·m.
   Net torque = 441 - 172 = 269 N·m in the first direction.
4. Given that 1 div = 0.1 mg, reciprocal sensitivity = 0.1 mg/div. Then, since E = 1/reciprocal sensitivity, $E = 1/0.1 = 10$ div/mg.
5. $E \propto L_p \Rightarrow E_1 = \text{const.}\ L_{p1}$, and $E_2 = \text{const.}\ L_{p2}$. Then,

$$\frac{E_2}{E_1} = \frac{\text{const.}\ L_{p_2}}{\text{const.}\ L_{p_1}} = \frac{L_{p_2}}{L_{p_1}}$$

   Using the given information,

$$\frac{E_2}{1.5} = \frac{45}{25} \Rightarrow E_2 = 2.7 \text{ div/g}$$

Test B-2

1. Torque = $Mg\ell$ = (0.030 kg) (9.8 m/s^2) (0.20 m) = 0.059 N·m. The torque will tend to rotate the system counterclockwise.
2. Clockwise torque = 2.50 N·m. Counterclockwise torque = 2.00 N·m. Net torque = 0.50 N·m. The system will rotate clockwise.
3. One direction: (15) (9.8) (2) + (40) (9.8) (0.5) = 490 N·m.
   Other direction: (40) (9.8) (1) = 392 N·m.
   Net torque = 490 - 392 = 98 N·m in the first direction.
4. Given that 1 div = 0.5 mg, recipro-

cal sensitivity = 0.5 mg/div. Then since E = 1/reciprocal sensitivity, $E = 1/0.5 = 2$ div/mg.

5. $\frac{E_2}{E_1} = \frac{L_{p_2}}{L_{p_1}}$

$\frac{E_2}{0.75} = \frac{15}{25} \Rightarrow E_2 = 0.45$ div/g.

Test C-1

1. (a) $\rho_E = 2\rho_W \qquad \rho_W = 2\rho_B$

$\rho_E = 2(2\rho_B) = 4\rho_B$

$M_E = M_B$

$\rho_E = 4\rho_B \Rightarrow M_E/V_E = 4M_B/V_B$

$\Rightarrow 1/V_E = 4/V_B \Rightarrow V_B = 4V_E$

(b) $\rho_W = 2\rho_B \Rightarrow M_W/V_W = 2M_B/V_B$

$M_B = M_W \Rightarrow 1/V_W = 2/V_B$

$\Rightarrow V_B = 2V_W$

(c) $\rho_E = 2\rho_W = M_E/V_E = 2M_W/V_W$

$V_E = V_W \Rightarrow M_E = 2M_W = M_W$

$\Rightarrow (1/2)\ M_E$

(d) $\rho_W = \rho_S \Rightarrow M_W/V_W = M_S/V_S$

$2V_W = V_S \Rightarrow M_W/V_W = M_S/2V_W$

$\Rightarrow M_S = 2M_W$

2. $M_S = 28.6935 \left[1 + 1.2 \times 10^{-3}\left(\frac{1}{11.3} - \frac{1}{8.02}\right)\right]$

$M_S = 28.6935 \left[1 + 1.2 \times 10^{-3}(-3.6 \times 10^{-2})\right]$

$= 28.6935 \left[1 - (4.3 \times 10^{-5})\right]$

$= 28.6935 - 0.0012$

$M_S = 28.6923$ g

3. $\bar{m} = \frac{\Sigma m_i}{N}$

$\bar{m} = \frac{4.494 \text{ g}}{6} = 0.749$ g

4. Best value for Balance A = (9.89 ± 0.02) g = 9.87 g to 9.91 g. Best value for Balance B = (9.76 ± 0.08) g = 9.68 g to 9.84 g.

These measurements are said to differ significantly, because their ranges of values do not overlap.

5. $E \propto \frac{1}{Md} \Rightarrow \frac{E_2}{E_1} = \frac{M_1d_1}{M_2d_2} \Rightarrow E_2 = E_1\left(\frac{M_1d_1}{M_2d_2}\right)$

Then $E_2 = 3.0\left[\frac{M_1d_1}{(3/2)M_1\ (1/2)d_1}\right]$

$= 3(4/3) = 4$

$E_2 = 4$ div/mg.

Test C-2

1. (a) $\rho = M/V \qquad M_{I.O.} = M_A \Rightarrow$

$\rho_{I.O.}V_{I.O.} = \rho_A V_A \Rightarrow V_{I.O.} =$

$= (\rho_A/\rho_{I.O.})V_A \Rightarrow V_{I.O.} =$

$(2.5/5)V_A \Rightarrow V_{I.O.} = 1/2\ V_A$

(b) $M_M = M_A \Rightarrow \rho_M V_M = \rho_A V_A \Rightarrow$

$V_A = (\rho_M/\rho_A)V_M \Rightarrow V_A =$

$(3/2.5)V_M \Rightarrow V_A = 1.2V_M$

(c) $V_M = V_{I.O.} \Rightarrow M_M/\rho_M =$

$\underline{M}_{I.O.}/\rho_{I.O.} \Rightarrow \underline{M}_{I.O.} =$

$(\rho_{I.O.}/\rho_{M})\underline{M}_{M} \Rightarrow \underline{M}_{I.O.} =$

$(5/3)\underline{M}_{M} \Rightarrow \underline{M}_{I.O.} = 1.67\ \underline{M}_{M}$

(d) $\underline{M}_1/\underline{V}_1 = \underline{M}_2/\underline{V}_2 \Rightarrow \underline{M}_1/\underline{V}_1 =$

$\underline{M}_2/2\underline{V}_1 \Rightarrow \underline{M}_2 = (2\underline{V}_1/\underline{V}_1)\underline{M}_1$

$\Rightarrow \underline{M}_2 = 2\underline{M}_1$

2. $\underline{M}_s = 3.4225 \left[1 + 1.2 \times 10^{-3}\left(\frac{1}{3.25} - \frac{1}{8.02}\right)\right]$
$= 3.4225 \left[1 + 1.2 \times 10^{-3}(0.18)\right]$
$= 3.4225 \left[1 + (2.2 \times 10^{-4})\right]$
$= 3.4225 + 0.00075$
$\underline{M}_s = 3.4233$ g

3. $\underline{\bar{m}} = \frac{\sum m_i}{N}$

$\underline{\bar{m}} = \frac{122.280 \text{ cm}}{6} = 20.380$ cm

4. Best value for Balance A = (17.54 ± 0.03) g = 17.51 g to 17.57 g. Best value for Balance B = (17.46 ± 0.007) g = 17.39 g to 17.53 g. These measurements are said not to differ significantly, because their ranges of values overlap.

5. $\underline{E} \propto \frac{1}{\underline{Md}} \Rightarrow \frac{\underline{E}_2}{\underline{E}_1} = \frac{\underline{M}_1\underline{d}_1}{\underline{M}_2\underline{d}_2} \Rightarrow \underline{E}_2 = \underline{E}_1\left(\frac{\underline{M}_1\underline{d}_1}{\underline{M}_2\underline{d}_2}\right)$

Then $\underline{E}_2 = 2.0\left[\frac{\underline{M}_1\underline{d}_1}{(4/3)\underline{M}_1\ (2/3)\underline{d}_1}\right]$

$= 2.0\ (9/8) = 2.25$

$\underline{E}_2 = 2\text{-}1/4$ div/mg.

IX LIST OF APPARATUS

<u>Experiment A-1</u>

Triple beam balance
Double pan, equal arm balance
Spring balance
Substitution-type, single pan analytical balance
Meter stick balance apparatus (1 set)
- Meter stick (1)
- Fulcrum apparatus (1)
- Adjustable pan supports (2)
- Weight holders (2)
- Weights (1 set)
- Wire basket weight holder (1)
- Support (1)
- Cardboard scale (1)
- Small weights (paper clips)
- Beaker (500 ml)
- Glass beads or marbles (20-30)

Cardboard sheet (20" x 30")
Pins (2)
Paper clips (2)

<u>Note</u>: If the meter stick balance apparatus is to be fabricated in your own lab, it is important that the fulcrum apparatus and pan supports be modified as shown in Figure 4 so that the fulcrum and the points at which weights are suspended are all at the same level, <u>along a line halfway between the edges of the meter stick</u> (so that the line passes through the center of mass of the meter stick). It is also important that the mass of the pointer above the fulcrum be the same as that of the supporting rod below the fulcrum. Under these conditions, the center of mass of the rigid beam system will be at the fulcrum, unless there are weights placed on the supporting rod below the fulcrum.

<u>Experiment B-1</u>

Meter stick balance apparatus
Adjustable pan support
Weight holder
Set of weights

<u>Experiment B-2</u>

Meter stick balance apparatus
Several (10-12) one-gram weights.

<u>Note</u>: Although these weights can be purchased as slotted weights, they are

too expensive. You can prepare inexpensive 1/2-gram weights by cutting 12 mm off a wire end of a standard #1 size paper clip. These paper clip weights will then have a mass of (0.50 ± 0.01)g.

Experiment C-1

Triple beam balance
Caliper (for measuring dimensions of objects)
Beaker (250 ml)
String (50 cm)

Experiment C-2

Substitution-type analytical balance
Pennies (10)
Piece of glass (2-10 g)
Piece of lead (50-100 g)

OPTIONAL DEMONSTRATION AIDS

Whenever possible, for discussions of experiments, questions, or problems, simple, short demonstrations are helpful.

16-mm Sound Films

1. "The Modern Balance," 16 min., color; Mettler Instrument Corp. (20 Nassau Street, Princeton, N.J. 08540).
2. "Mass and Weight," 11 min., color; Coronet Films (Chicago, Ill.).
3. "The Balance and Its Uses," 18 min., color; Imperial Chemical Industries, Inc. (New York).
4. "Buoyancy," 14 min., color; Bailey-Film Associates (Los Angeles, Calif.).
5. "Inertial Mass," 19 min., B & W; Modern Learning Aids (New York, N.Y.).
6. "Single Pan Balance," 5 min., color; Encyclopedia Britannica Educational Corp. (Chicago, Ill.).

8 mm-Film Loops

1. "Mettler H8 Weighing Instructions," Mettler Instrument Corp. (Available for preview before purchase.)
2. "Newton's Third Law," Ealing Corp. (Cambridge, Mass.).
3. "Simple Machines: The Action of the Lever I," E.B.E. Corp.
4. "Analytical Balance: Tare Weight Determination," E.B.E. Corp.
5. "Analytical Balance: Weighing Sample and Container," E.B.E. Corp.

Overhead Transparencies

1. "Substitution Weighing Theory," Mettler.
2. "How to Read an Analytical Balance Optical Scale with Vernier," Mettler.
3. "Torque Arms Are Measured along Perpendicular Lines," Frey Scientific Company, No. 6814.
4. "A First-Class Lever," Frey Scientific Company, No. F-6732.

CONTENTS

I INTRODUCTION

The primary purpose of this module is to introduce the concept of momentum and to establish momentum conservation and energy conversion considerations as useful principles in the study of collision phenomena. On the way, we discuss elementary kinematics, dynamics, and statics.

Only the most basic kinematical concepts are treated. We deal mainly with uniformly accelerated straight-line motion and the rotation of rigid bodies at constant angular velocity about a fixed axis of symmetry. Operational definitions of mass and force are presented, and a description of the results of an experiment to verify Newton's second law is included. We have not asked the students to perform experiments or do problems on $\underline{F} = \underline{ma}$, because this law plays a supportive rather than a central role in this module.

Torque is defined with some care, and the conditions for equilibrium are discussed at length. There are both experiments and problems involving rigid bodies at rest. Several of our objectives are concerned directly with the concepts of statics. We focus attention strongly on the center of mass concept because it provides a link between the sections on statics and those on collisions.

Momentum conservation in two-body collisions is first suggested by simple experiments, then predicted from Newton's laws, and finally verified through careful measurement of before and after velocities in two-body collisions. The latter are simulated on film; we did not discover a more economical way to obtain convincing data. There is also an extensive discussion of the damage that results from automobile collisions. (The students will enjoy the short film showing real collisions.) We treat the role played by the strength of materials qualitatively and the conversion of kinetic energy to heat somewhat more quantitatively.

There was a deliberate attempt to present these concepts in a helical style. In the first cycle, ideas have been introduced in words and with crude experiments. In the second cycle, some equations are derived and the experiments are more quantitative. We hope this approach will be welcomed by students and not too disorienting for teachers who are accustomed to a more logical presentation.

II SPECIAL PREREQUISITES

Although there are no special prerequisites, the module is relatively sophisticated. Thus it might best be used after one of the other mechanics modules, such as The Analytical Balance or The Stroboscope.

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Appendix: Center of Mass and Torque Revisited

IV GOALS

After completing each section of the module, the student should be able to do the things in the following lists.

Section A.

1. Define the following technical terms both in words, and if appropriate, in mathematical language: average velocity, uniform motion, acceleration, uniformly accelerated motion, angular velocity (frequency of revolution), period (for uniform rotational motion), mass, force, center of mass, lever arm, torque, kinetic energy, gravitational potential energy, elastic potential energy, heat energy.

2. Given position versus time data for an object undergoing uniformly accelerated motion, determine the acceleration by using measurements made on appropriate graphs you plot.

3. Knowing the mass of an object and the forces acting on it, calculate its acceleration.

4. Given a rigid object that you can lift, such as a board or a meter stick, determine the location of the center of mass.

5. Knowing all the forces on an object and their points of application, calculate the torques produced by these forces. Determine from the sum of these torques whether or not the object is undergoing a rotational acceleration.

Section B.

1. Define momentum and state the law of Conservation of Momentum.

2. Given the mass and velocity of a moving body, calculate its momentum and kinetic energy.

3. Given the masses and velocities of two bodies before they experience a head-on inelastic collision, calculate the total momentum of the system, the velocity of the system after the collision, and the amount of kinetic energy lost during the collision.

Section C.

1. Define stress and elastic limit.

2. Given the values and locations of several small masses, calculate

the location of the center of mass of the system.

3. Given the average value of the force on a body or a system of bodies and the time interval during which the force acts, calculate the impulse of the force and the change of momentum of the system that experiences the force.

4. Discuss at least two processes by which kinetic energy lost in an automobile collision can be converted to forms that do not result in damage to the cars involved.

5. Describe two techniques for minimizing the destructive effect of "second collisions" on the participants in an auto accident and know the physical principle responsible for their effectiveness.

V DISCUSSION OF ACTIVITIES

Different institutions have different arrangements for class and laboratory meetings. Therefore it is not possible to establish a schedule which would be appropriate for all. If you are limited in laboratory time, you may choose to do some of the experiments as demonstrations. For example, Experiment A-3, Locating the Center of Mass of an "Automobile", would be a nice demonstration of equilibrium. Experiment A-2, Locating Centers of Mass, and Experiment B-1, Collisions with Carts, definitely should be done by the students.

The activities in this module center on the experiments. Experiment A-1 is an introduction to one-dimensional kinematics. It provides the students with working knowledge of the basic quantities used to describe motion.

Experiment A-2 is a series of methods for locating the center of mass of an object. Not all of them are practical in the sense of providing a convenient, accurate measurement, but each of them is based on an important characteristic of the center of mass. In doing the experiments the student becomes better acquainted with the meaning and significance of the center of mass.

In Experiment A-3 the student locates the center of a mass of an object representing an automobile. Basically this is an equilibrium problem in which the two coordinates of the center of mass of a plane object are unknown. Measuring the two support forces for each of two orientations of the object enables the center of mass to be determined.

Experiment B-1 involves observations of the motion of a cart when students jump on and off it in a variety of ways. Although the accuracy is limited it is sufficient to develop a feeling for momentum and to make believable the idea of conservation of linear momentum.

In Experiment B-3 the student makes measurements from a film which shows simulated collisions between an automobile and a truck. This approach has the disadvantage of being a "fake", because the collisions are simulated. However there is a definite advantage in being able to avoid the usual experimental difficulties met in real collisions. This enables the student to do more cases than possible if real collisions were used.

Experiment C-1 is performed with gliders on an air track. One glider has an attachment that consists of a sleeve loaded with a spring and a plunger. When a collision occurs, a ratchet on the sleeve catches the plunger at the point of maximum compression, thereby providing a measure of the maximum force exerted during the collision. A series of experiments shows why seat belts reduce injuries.

VI SAMPLE DATA

Exp. A-1. Uniform motion: Analysis for Figure 3B. Strobe rate is 10 flashes per second. Distance units are those shown in the photo.

t(s)	S(units)	d(units)	V(units/s)
0	13.8		
		13.7	137
.1	27.5		
		13.6	136
.2	41.1		
		13.4	134
.3	54.5		
		13.3	133
.4	67.8		
		13.4	134
.5	81.2		

Accelerated motion: analysis for Figure 4B. Strobe rate is 10 flashes per second. Distance units are those shown in the photo.

t(s)	S(units)	d(units)	V(units/s)
0	.9		
		1.7	17
.1	2.6		
		2.2	22
.2	4.8		
		2.4	24
.3	7.2		
		3.0	30
.4	10.2		
		3.8	38
.5	14.0		
		3.8	38
.6	17.8		
		4.2	42
.7	22.0		
		4.9	49
.8	26.9		
		5.2	52
.9	32.1		
		6.0	60
1.0	38.1		
		6.5	65
1.1	44.6		
		6.9	69
1.2	51.5		
		7.4	74
1.3	58.9		
		7.9	79
1.4	66.8		
		8.2	82
1.5	75.0		
		8.7	87
1.6	83.7		

If these data are plotted, the slope of the velocity versus time graph gives a value of about 47 units/s^2.

Exp. A-2. The best way to check the experimental results is to see how well the different methods agree.

Exp. A-3. The results will depend on the details of the apparatus and the location of the "motor" mass. The following represents one set of data. (Refer to Figures 29 and 30 in the module.)

$F_A = 7.9$ N

$F_B = 7.2$ N

$L_1 = 49.6$ cm

$$X_1 = \frac{F_B}{F_A + F_B} L_1 = 23.7 \text{ cm}$$

With the board tilted,

$F_C = 9.5$ N

$F_D = 5.5$ N

$L_2 = 47.3$ cm

$$X_2 = \frac{F_D}{F_C + F_D} L_2 = 17.3 \text{ cm}$$

The intersection of the two lines is the location of the center of mass.

Exp. B-1.

The students should be thoroughly cautioned to be very careful in performing this experiment. The natural tendency toward horse play must be suppressed or serious injuries can occur. Practice trials at slow speeds are recommended before collecting data.

Your numerical results may differ considerably from those described below because of difference in apparatus and technique.

Step 1: 10 m.
Step 2: 20 m. With the faster speed of approach, the cart and person after collision have more momentum and go farther than in Step 1.
Step 3: 12 m. The more massive person will have more momentum than the lighter person at the same speed. The cart and person go farther than in Step 1. (One way to match the speeds of the people in Steps 1 and 3 is to have the lighter person run beside the heavier person trying to duplicate the same speed as in Step 1.)
Step 4: 5 m. The initially stationary system of cart plus person is more massive than the cart alone. The cart plus person system is given the same momentum as was the cart alone in Step 1. Therefore the velocity of the cart plus two persons is smaller and the distance is shorter than in Step 1.
Step 5: 10 m. When the person jumps on, his momentum is transferred to a system consisting of the two persons and the cart as it was in Step 4. However, in order to jump off again, the person must exert a force on the cart, giving it (and its occupant) an additional increase in forward momentum, so that it gains more momentum and goes farther than in Step 4. (Of course, to do this, the cart must exert an equal and opposite force on the person jumping, who then gains a backward momentum equal and opposite to the additional increment of the cart's forward momentum.)
Step 6: One person jumps: 7 m; both jump: 23 m. Change in momentum forward = - change in momentum rearward. When the case where both persons jump is compared to the single person's jump, it is clear that an increased mass acquires the same rearward velocity, roughly doubling the rearward momentum, and at the same time the forward moving mass is greatly reduced, resulting in a much larger cart velocity.
Step 7: Same direction (same as in part 2 of Step 6): 23 m; opposite directions: 0 m. Change in momentum forward = - change in momentum rearward. When persons of comparable masses jump in opposite directions with comparable speeds, they will nearly balance the momentum conservation equation without any motion of the cart. The cart may move slightly if the jumpers do not have identically equal and opposite momenta.
Step 8: Maximize height of jump: 2.4 m; maximize distance of jump: 17 m. Only the horizontal component of the jumper's force gives the cart its momentum (because the normal force of the ground is acting as an external force in the vertical direction) so the momentum of the cart is maximized if the horizontal component of the force that the jumper exerts on the cart is maximized.
Step 9: While the person walks the cart moves in opposite direction, but stops when person stops. Both are displaced from the original position. The less massive object is displaced the larger amount. It can be pointed out that in all the earlier steps, the cart starts to move as soon as the jumper does. At all times the momenta are equal and opposite. The same principles apply when walker slows down, the force to slow the walker must be exerted by cart, with an equal and opposite force slowing the cart.

Exp. B-2.

Part 1

Before Collision: Car: $\underline{X}_1 = -65m$ $\underline{X}_2 = -25m$ $\Delta\underline{t} = 2.0s$

After Collision: Car & Truck: $\underline{X}_1 = 15m$ $\underline{X}_2 = 35m$ $\Delta\underline{t} = 3.0s$

	Before Collision			After Collision	Difference Between Before and After
	Car	Truck	Total		
Velocity (m/s)	20	0	N.A.	6.7	N.A.
Momentum (kg·m/s)	$4.0x10^4$	0	$4.0x10^4$	$4.0x10^4$	0
Kinetic Energy (J)	$4.0x10^5$	0	$4.0x10^5$	$1.34x10^5$	$2.66x10^5$ $\Delta\underline{k}/\underline{k}_i = 67\%$

Part 2

Before Collision: Car: $\underline{X}_1 = -70m$ $\underline{X}_2 = -10m$ $\Delta\underline{t} = 2.0s$

Truck: $\underline{X}_1 = -15m$ $\underline{X}_2 = 15m$ $\Delta\underline{t} = 2.0s$

After Collision: Car and Truck: $\underline{X}_1 = 40m$ $\underline{X}_2 = 80m$ $\Delta\underline{t} = 2.0s$

	Before Collision			After Collision	Difference Between Before and After
	Car	Truck	Total		
Velocity (m/s)	30	15	N.A.	20	N.A.
Momentum (kg·m/s)	$6.0x10^4$	$6.0x10^4$	$12.0x10^4$	$12.0x10^4$	0
Kinetic Energy (J)	$9.0x10^5$	$4.5x10^5$	$13.5x10^5$	$12.0x10^5$	$1.5x10^5$ $\Delta\underline{k}/\underline{k}_i = 11\%$

Part 3

Before Collision: Car: $\underline{X}_1 = -90m$ $\underline{X}_2 = -30m$ $\Delta\underline{t} = 2.0s$

Truck: $\underline{X}_1 = 45m$ $\underline{X}_2 = 15m$ $\Delta\underline{t} = 2.0s$

After Collision: Car & Truck: $\underline{X}_1 = \underline{X}_2$

	Before Collision			After Collision	Difference Between Before and After
	Car	Truck	Total		
Velocity (m/s)	30	-15	N.A.	0	N.A.
Momentum (kg·m/s)	6.0×10^4	-6.0×10^4	0	0	0
Kinetic Energy (J)	9.0×10^5	4.5×10^5	13.5×10^5	0	13.5×10^5 $\Delta\underline{k}/\underline{k}_i = 100\%$

Part 4

Since the first collision shown is the collision of Part 1 viewed in the center of mass frame, all velocities are reduced by the velocity of the center of mass; 6.7 m/s.

Before Collision: Car: $\underline{X}_1 = -55m$ $\underline{X}_2 = -29m$ $\Delta\underline{t} = 2.0s$

This gives a velocity of 13 m/s, while the calculated value is 13.3 m/s. The following table is based on values calculated from Part 1 data.

	Before Collision			After Collision	Difference Between Before and After
	Car	Truck	Total		
Velocity (m/s)	13.3	-6.7	N.A.	0	N.A.
Momentum (kg·m/s)	2.6×10^4	-2.6×10^4	0	0	0
Kinetic Energy (J)	1.77×10^4	$.90 \times 10^4$	2.67×10^5	0	2.67×10^5 $\Delta\underline{k}/\underline{k}_i = 100\%$

(Note that the loss in kinetic energy is independent of the frame of reference.)

Part 4b

Compared to Part 2, all velocities are reduced by the velocity of the center of mass; 20 m/s.

	Before Collision			After Collision	Difference Between Before and After
	Car	Truck	Total		
Velocity (m/s)	10	-5	N.A.	0	N.A.
Momentum (kg·m/s)	2.0×10^4	-20×10^4	0	0	0
Kinetic Energy (J)	1.00×10^5	$.50 \times 10^5$	1.50×10^5	0	1.50×10^5 $\Delta \underline{k}/\underline{k}_i$ = 100%

Part 5

Before Collision: Car: $\underline{X}_1 = -90$m $\underline{X}_2 = -30$m $\Delta\underline{t} = 2.0$s

Truck: $\underline{Y}_1 = -60$m $\underline{Y}_2 = -20$m $\Delta\underline{t} = 2.0$s

After Collision: Car and Truck: $\underline{S}_1 = 25$m $\underline{S}_2 = 60$m $\Delta\underline{t} = 2.0$s

	Before Collision			After Collision	Difference Between Before and After
	Car	Truck	Total		
Velocity (m/s)	30	20		17	
Momentum (kg·m/s)	6.0×10^4	8.0×10^4	*10.0×10^4	10.2×10^4	0.2×10^4
Kinetic Energy (J)	9.0×10^5	8.0×10^5	17.0×10^5	8.6×10^5	8.6×10^5 $\Delta \underline{k}/\underline{k}_i$ = 50%

* $\sqrt{6^2 + 8^2} = 10$

Exp. C-1.

Part 1: Different Velocities

Use the smaller spring constant, large area self-gripping pad, leave room for 3 gliders, and keep the angle of the track small enough so that the plunger will not bottom out in Part 2 with 3 gliders.

Step 1: Spring Constants

k_1 = 280 N/m k_2 = 49 N/m

Step 2: Initial Plunger Position

Glider #1: d_o = 2.7 cm

Glider #2: d_o = 2.1 cm

Step 3-9: Glider #2, d_o = 2.1 cm, h_f = 25.1 cm above table, k = 49 N/m, m = .2012.

	h_o(cm)	Δh(cm)	P(kg·m/s)	d_f(cm)	$d_o - d_f$	F_{av}(N)	t(s)
¼ track	25.8	.7	.075	1.4*	.7	.17	.441
½ track	26.5	1.4	.11	1.1*	1.0	.25	.440
full track	27.9	2.8	.15	.3*	1.8	.44	.341

*Average for several trials.

Part 2: Different Masses

Glider #2 used for lead glider, d_o = 2.3 cm, $\Delta h = h_o - h_f$ = .3 cm.

m(kg)	V(m/s)	P(kg·m/s)	d_f(cm)	$d_o - d_f$	F_{av}(N)	t(s)
.2012	.244	.049	1.8	.5	.12	.41
.4030	.243	.098	1.0	1.3	.32	.31
.5958	.252	.15	.1	2.2	.54	.28

Part 3: Stronger Spring

Glider #1, d_o = 2.7 cm, k = 28 N/m, m = .2018 kg.

Δh(cm)	P (kg·m/s)	d_f(cm)	$d_o - d_f$	F_{av}(N)	t(s)
.3	.049	2.3	.4	.56	.089

Part 4: Different areas of contact pads. No measurable difference from Part 1.

Part 5: Simulated seat belts. Use stronger spring in the glider that represents the "car" rather than the weaker as called for in the module.

Step 1: $\Delta \underline{h} = .01$ m, $\underline{m} = .2012$ kg

$\underline{p} = .088$ kg·m/s

$\underline{d}_o = 2.2$ cm, $\underline{d}_f = 0.5$ cm

$\underline{F}_{av} = 0.42$ N

$\underline{t} = \underline{p}/\underline{F}_{av} = .21$s

Step 2: $\Delta \underline{h} = .01$ m, $\underline{m} = .0212$ kg

$\underline{p} = .088$ kg·m/s

$\underline{d}_o = 2.2$ cm, $\underline{d}_f = 1.3$ cm

$\underline{d}_o - \underline{d}_f = .9$ cm

$\underline{F}_{av} = 0.22$ N

$\underline{t} = \underline{p}/\underline{F}_{av} = .4$s

VII SOLUTIONS TO PROBLEMS

1. (a) 4 min. (The four consecutive 36 pole counts.)
   (b) 26 m/s
   (c) 24.7 m/s
   (d) 24.3 m/s
2. $\underline{t}_{up} = 0.167$ h $\quad \underline{t}_{down} = 0.1$ h
   $\underline{V}_{av} = 37.5$ mi/h
3. (Problem 3 is missing in first edition of the student module. The instructor may wish to add a problem on Newton's second law.)
4. (a) 7.5 m/s
   (b) 0.12 s
   (c) 125 m/s^2
   (d) 10,000 N
5. (a) 3 ft
   (b) 1000 lb
6. When level, CM lies on a vertical line 6.11 ft from the rear wheels (3.89 ft from the front wheels). When raised, the CM lies on a vertical line 5.84 ft from the rear wheels (3.16 ft from the front wheels). The intersection of the two lines is about 9 inches above the road line (probably too low to be realistic).
7. This is similar to "pulling yourself up by your bootstraps". Just as an <u>external</u> force opposite to the force of gravity must be exerted in order to lift your weight, in this case an <u>external</u> torque must be applied to lift the end of the truck. The internal torque developed by the hoist will not lift the truck; it can only bend the bumper or the hoist.
8. (a) 12,500 J
   (b) 12,500 J
   (c) 12,500 J
9. After the first person jumps, the cart will be moving at 2.7 m/s. After the second jumps, the cart will be moving at 10.7 m/s.
10. (a) $\underline{P} = 324$ kg·m/s
    $\underline{KE} = 729$ J
    (b) $\underline{P} = -360$ kg·m/s
    $\underline{KE} = 900$ J
    (c) $\underline{P} = 684$ kg·m/s
    $\underline{V} = 6.33$ m/s
    $\underline{KE} = 2166$ J
    (d) $\Delta\underline{KE} = 2337$ J. This came from the work done by the muscles of the jumper pushing against the cart as he jumped on and off.
11. (a) 9 kg·m/s
    (b) 200 N

Appendix 1. 1213 on each rear wheel
1097 on each front wheel

Appendix 2. 0.26 ft.

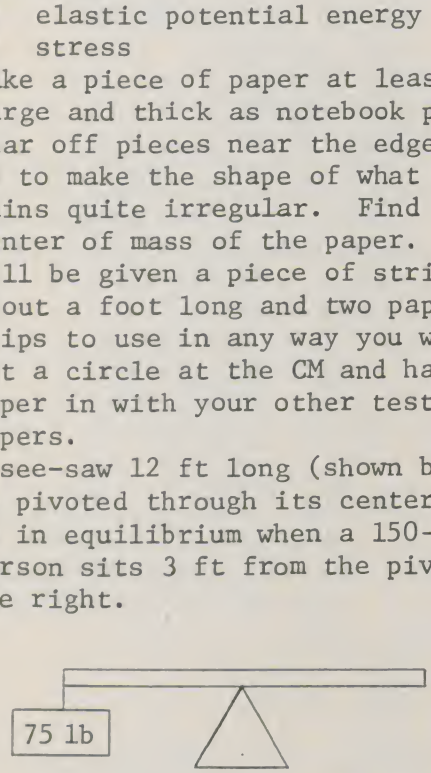
VIII POST-TESTS

The following are two sample Post-Tests to evaluate student performance on this module. Clearly, each is too long for a 50-minute exam period. Either the exam period must be lengthened or the number of questions requiring answers decreased. It is expected that about five questions

would constitute an hour exam, so several tests could be constructed from the following two tests. The tests do not include problems on material covered in the Appendix.

Test A

1. Define the following terms both in words and, if appropriate, in mathematical language.
   a) average velocity
   b) torque
   c) elastic potential energy
   d) stress
2. Take a piece of paper at least as large and thick as notebook paper. Tear off pieces near the edges so as to make the shape of what remains quite irregular. Find the center of mass of the paper. (You will be given a piece of string about a foot long and two paper clips to use in any way you wish.) Put a circle at the CM and hand the paper in with your other test papers.
3. A see-saw 12 ft long (shown below) is pivoted through its center. It is in equilibrium when a 150-lb person sits 3 ft from the pivot on the right.



   Write down the conditions of equilibrium and show by direct calculation that the torques about the left end of the see-saw sum to zero.
4. A car of mass 1000 kg has initially a velocity of 10 m/s north. Later the same car has a velocity of 20 m/s south.
   a) What is the change of momentum?
   b) What is the change of kinetic energy?
5. A car 5 ft high is at rest with its front wheels on a spring scale that reads 900 lb and its rear wheels, 10 ft farther back, on another spring scale that reads 600 lb. Later the car is in a slight accident and ends on its side. The wrecker attaches a rope to the roof of the car and pulls straight up. It just manages to begin to lift the top and thus return the car toward an upright position when the upward force of the rope reaches 600 lb. What is the weight of the car and where is its center of gravity with respect to the lowest point of the front wheels (when the car is upright)?
6. Write the formulas for the momentum and kinetic energy of a person of mass m on a merry-go-round at an instant when the velocity of the person is v north. Indicate the direction only when it is necessary for a complete description of the quantity specified.
7. A car of mass 1000 kg moving north at 20 m/s collides with and sticks to a truck of 2000 kg moving south at 15 m/s. It is a head-on collision. If there is no friction, what is the velocity of the wreckage?
8. A stationary car is struck by a moving car such that before the collision the center of mass of one moves directly at the CM of the other. This collision is repeated with identical cars and velocities except that the collision point is such that they spin around wildly after collision. In which collision is more heat formed and why?
9. Consider two kinds of springy metal from which bumpers can be made. Bars of identical size are made from each metal, clamped at one end, and forces are exerted perpendicular to the bars at the other end. When a force of 10 N is applied to metal A, the end

bends through 10 cm but returns to its original position when the force is removed. When the same force is applied to metal B, the end bends through 3 cm but returns only 2 cm.

a) Which metal is stronger?
b) Which metal is more elastic?
c) If you wanted to build bumpers to avoid damage in low-speed collisions, which metal would you use?
d) If you wanted to reinforce the passenger compartment to protect against high-speed collisions, which metal would you use?

10. A brick of weight 20 N is acted on by gravity 3.0 seconds.
    a) What is the impulse on the brick during this time?
    b) What is the momentum change of the brick during this time?
    c) The mass of the brick is 2 kg. If its velocity at the beginning of the 3-second interval was 10 m/s up, what is its velocity at the end of the interval?

11. A car is moving 24 m/s when the driver applies the brakes. The car decelerates uniformly to a stop while moving a distance of 36 meters past the point where the brakes were applied. The mass of the car plus contents is 2000 kg. The driver has a mass of 60 kg and is wearing her seat belt. Find:
    a) the time required to stop
    b) the braking force on the car
    c) the force exerted by the seat belt on the driver

12. The table below shows the observed positions and times for a glider moving down an air track.

t(s)	x(cm)
0.2	3.8
0.4	10.9
0.6	21.3
0.8	35.3
1.0	52.8
1.2	73.7
1.4	97.8

By plotting an appropriate graph and making measurements from it, determine the acceleration (assumed to be constant).

Test B

1. Define the following terms both in words and, if appropriate, in mathematical language:
    a) acceleration
    b) center of mass
    c) kinetic energy
    d) gravitational potential energy

2. A car is moving at 30 m/s when the driver applies the brakes. The mass of the car plus contents is 2000 kg and the braking force exerted on the car is 10,000 N. The driver has a mass of 80 kg and is wearing his seat belt. Find
    a) the deceleration of the car
    b) the time required to stop
    c) the distance required to stop
    d) the force exerted by the seat belt on the driver.

3. A broken meter stick is repaired by splicing the break with a metal sheath, thus shifting the center of mass away from the 50-cm mark. To locate the CM, a student makes the following measurements: (1) the end at 0 is supported by the edge of a table and the end at 100 cm by a delicate spring balance that reads 3.5 ounces when the stick is in a horizontal position; (2) the ends are now reversed, and with the spring balance supporting the end at 0, it reads 6.5 ounces. Where is the CM?

4. Indicate which of the following sentences describe a body in equilibrium.
    a) A marble falls at constant velocity through a vat of oil.
    b) A car with its brakes on slides and turns as it moves

across a horizontal, frictionless sheet of ice.

c) A ball thrown straight up in the air reaches the peak of its rise and stops momentarily before falling down again.

d) A car rolls down a hill through loose sand at constant velocity.

e) The power to a grinding wheel has been shut off and the wheel gradually slows down.

5. A car with mass 1500 kg is moving at constant speed down a straight road. It passes one check point when a stop watch is started and passes another 1.6 kilometers down the road where the stop watch reads 1 minute and 20 seconds. Find
   a) the velocity of the car
   b) the momentum of the car
   c) the kinetic energy of the car

6. A car of mass 1000 kg going north at 40 m/s collides with a car of mass 1500 kg going east at 20 m/s. The collision is completely inelastic.
   a) What is the magnitude of the velocity of the wreckage?
   b) Does the wreckage move in a direction north of northeast or east of northeast?

7. A hockey puck is slammed along the ice and strikes a hockey stick lying perpendicular to the path of the puck. There is a wad of gum marking the center of mass of the stick, and the puck strikes this gum and sticks to it. In a second trail of the same sort, the same puck moving with the same velocity strikes the same stick, which is again lying perpendicular to the motion of the puck. This time the collision is near the end of the stick, but again there is gum and the puck sticks to the stick.
   a) Compare the momentum of the system after collision for the two cases.
   b) In which case is the amount of heat energy generated greater?

8. A soccer ball of mass 1.5 kg at rest is kicked so as to give it an impulse of 15 newton-seconds north. Before it has slowed down at all, an opposing player in the exact center of the field deflects it with an impulse directed 60° east of south with magnitude 24 newton-seconds.
   a) What was the velocity of the ball after the first kick?
   b) Was the opponent successful in his efforts to stop all northward motion of the ball?
   c) If the field is square and no one else touches the ball, what boundary line will it cross?

9. A car of mass 1000 kg moving north at 20 m/s collides head-on with a truck of mass 2000 kg moving south at 10 m/s. The collision is completely inelastic.
   a) How much heat (in joules) is produced in the collision?
   b) The same truck is moving north at 10 m/s and hits the same car moving north at 40 m/s directly from behind. The collision is totally inelastic. Can you say, without doing lengthy calculations, how much heat would be generated in this collision? How?

10. Describe two techniques for minimizing the destructive effect of "second collisions" on the participants in an auto accident, explaining the physical principles responsible for their effectiveness.

11. The following table shows the observed positions and times for a glider moving down an air track.

t(s)	x(cm)
0.2	7.8
0.4	22.0
0.6	42.8
0.8	70.8
1.0	105.8
1.2	147.6
1.4	195.8

By plotting an appropriate graph, and making measurements from it, determine the acceleration (assumed to be constant).

12. Discuss at least two processes by which kinetic energy lost in an automobile collision can be converted to forms that do not result in damage to the cars involved.

Answers to Post Tests

Test A

4. (a) 30,000 kg·m/s south
   (b) 1.5×10^5 J
5. W = 1500 lb
   4 ft back, 2 ft up
6. $P = m \cdot v$ north
   $K = \frac{1}{2} m \cdot v^2$
7. 3.33 m/s
8. More heat in first collision. In the second collision some of the lost translational kinetic energy appears in the form of rotational kinetic energy.
9. (a) B
   (b) A
   (c) A
   (d) B
10. (a) 60 N·s
    (b) 60 kg·m/s
    (c) 40 m/s
11. (a) 3 s
    (b) 16,000 N
    (c) 480 N
12. 85 cm/s^2

Test B

2. (a) 5 m/s^2
   (b) 6 s
   (c) 90 m
   (d) 400 N
3. 35 cm
4. a, b, and d.
5. (a) 20 m/s
   (b) 3×10^4 kg·m/s
   (c) 4.8×10^6 J
6. (a) 20 m/s
   (b) North of northeast
7. (a) Linear momentum is the same for the two cases.
   (b) More heat is generated in the first trial.
8. (a) 10 m/s north
   (b) No
   (c) The east boundary
9. (a) 3×10^5 J
   (b) 3×10^5 J. Viewed from CM, the two collisions are identical.
11. 170 cm/s^2

IX LIST OF APPARATUS

Experiment A-1

Air track with blower, such as Thornton ATT-100 and ABU-100.
Gliders
Stroboscope (e.g. Thornton STS-300) with self-developing camera, or spark-tape system.

Experiment A-2

Irregular piece of plywood with several holes near edges.
Meter stick
Laboratory masses
Tape
Hammer

Experiment A-3

Plywood board shaped like a car, with provision for attaching a laboratory mass to simulate the engine.
Two spring balances

Experiment B-1

Flat bed cart, such as used in warehouse or receiving department.

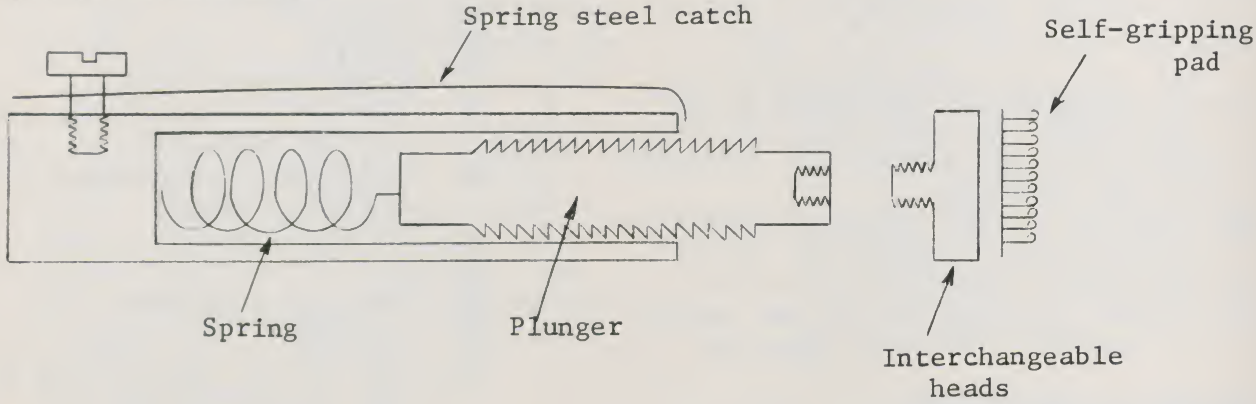
Experiment B-2

Film loop "Totally Inelastic Auto Collisions". (This film, and the

film loop on real auto collisions, "Crashworthiness", will be available from Thornton Associates.)

Experiment B-3

Air track with blower
Two gliders with force-measuring plunger attachment.



CONTENTS

I INTRODUCTION

The Automobile Ignition System module covers magnetism, electromagnetism, and electromagnetic induction. The practical devices that utilize these concepts--self and mutual inductance--are used along with capacitors and resistors in a study of circuits that exhibit exponential decay or growth, and oscillations.

II SPECIAL PREREQUISITES

This module requires that the student be familiar with Ohm's law and elementary concepts needed to understand capacitance.

These topics are covered in the Cathode Ray Tube module.

III TABLE OF CONTENTS OF THE MODULE

The Firing Section
Intermediate Section
Experiment C-1. An Analysis of the Ignition System

Transistorized Ignition System (Optional)

Work Sheets

Appendix: The Oscilloscope

IV GOALS

The objectives of the Automobile Ignition System module have been included at the beginning of each section of the module.

V DISCUSSION OF ACTIVITIES

The module is divided into three sections, each representing one week's study.

SECTION A

The first section begins with a cursory inspection of the ignition system. Students are then led through a series of steps--each step involving experiment and conclusion--until they have covered the fundamental classical ideas of magnetism, electromagnetism,and electromagnetic induction.

Experiment A-1. The Ignition System

The purpose of this experiment is to familiarize students with the princial components of the ignition system of an automobile. The student identifies the components and observes the sparking action at the plug while turning the rotor shaft by hand and, finally, when the rotor shaft is driven at engine speeds.

This experiment is supposed to raise questions abou the physics of the ignition system. Although most of these questions are answered through observations or descriptively in the module, the questions are not yet quantitative. Most of the quantitative and analytical material of the module is based on the qualitative observations students make in this experiment.

Experiment A-2. Magnetism and Electromagnetism

The purpose of this experiment is to study the effects of permanent and electromagnets. Students investigate the effects of a magnet on a compass needle and iron filings that are placed near the magnet. These investigations lead to the idea of a magnetic field. Students also study the effects of a changing field on a coil of wire in a closed electrical circuit.

SECTION B

Section B starts with a very simple circuit (one battery, one resistor, and one switch) using the oscilloscope as explained in the appendix. With progressively increasing complexity, various circuits are studied until the complete LRC circuit, including mutual inductance effects, is used as the section's conclusion.

Experiment B-1. Electrical Characteristics of Ignition System Components

The purpose of this experiment is to determine the effect that each component of the ignition system has on the variation of the voltage with time. The student learns to use the oscilloscope as a voltage and time measuring device. The transient behavior of inductive and capacitive components is studied qualitatively from the oscilloscope traces.

Experiment B-2. Secondary Voltage

The purpose of this experiment is to measure the high voltage in the secondary of the ignition system and to examine the factors which affect that voltage.

SECTION C

Section C might be called "The Automobile Ignition System Revisited."

A much more sophisticated approach to the ignition system is made possible by the students' newly gained understanding.

Without use of circuit analysis, students did not have a model with which to compare the experimental measurements. However, there are several different ways of arriving at the same numerical value for a particular parameter. The demand that these independent ways result in answers that reasonably agree gives authority to the final experimental results and allows students to check their experimental care and numerical accuracy. Some simplifying assumptions have been made regarding the automobile ignition system, in order that the student not be overwhelmed with complexity.

There is only one experiment in Section C.

Experiment C-1. An Analysis of the Ignition System

The purpose of this experiment is to analyze the oscilloscope traces of the primary and secondary circuits of the ignition system. The voltage and time measurements from these traces are related to derived quantities in the text.

VI SAMPLE DATA

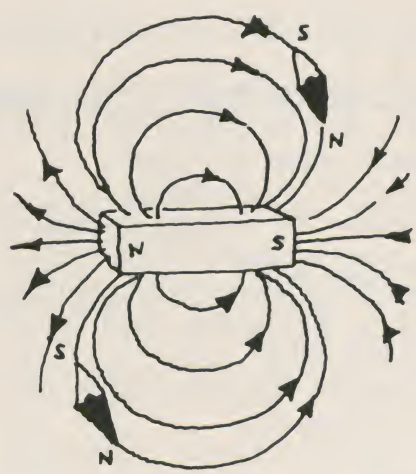
Experiment A-1

1. The conduction path of the high voltage is from the secondary terminal on the coil to the center terminal of the distributor cap, through a sliding metal-on-carbon contact to the rotor, then by a small spark across the rotor tip to the individual spark plug terminals.
2. Either 6 or 8 (once for each cylinder).
3. Spark occurs when the points open.
4. Yes, a small spark can be seen.
5. Without the capacitor, the spark at the points is much stronger while the useful spark at the plugs is much weaker.
6. Yes--proper firing order synchronizes the spark with the piston positions and valve operation, and also distributes the impulsive forces on the crankshaft in such a way as to minimize vibrational effects.
7. It is difficult to detect a change.

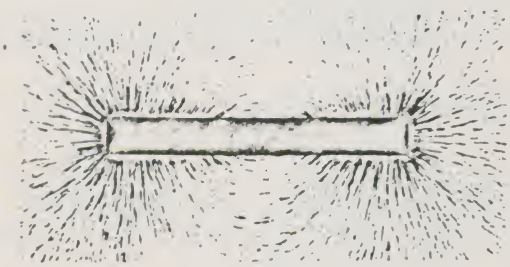
Experiment A-2

Part I: Magnetism

1. Attraction is the strongest near the ends.
2. No force is noted.
3. Iron objects tend to adhere, other metal objects do not.
4. Each half acts as the original magnet--it has attractive centers on the ends and none in the middle.
5. There is nothing tangible or visible, but clearly there are differences giving rise to attraction or repulsion. Any way to label (plus and minus, North and South, A and B) would give rise to the likes-unlikes rule.
6. The same pole always points toward the Alaskan direction. Since we mark this the North (or North-seeking pole) it must be that the earth's North geographic pole is really a South magnetic pole.
7. They align with the North on one above the South on the other.
8. The earth acts like a magnet.
9. With a consistent scheme for labeling, the like and unlike rule applies for all experiments.
10.



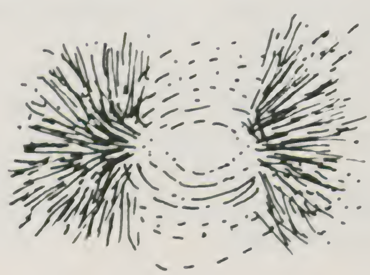
11.



12. Yes.
13. The needle will be parallel with the filings.

Part II: Electromagnetism

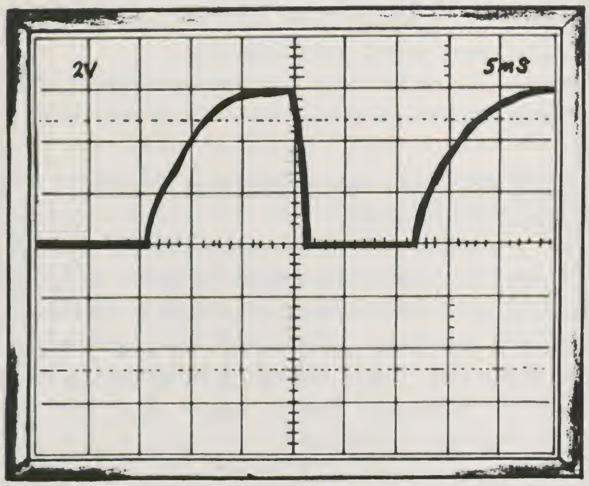
1. The spot deflects downwards.
2. The spot deflects upward.
3. As the distance increases, the deflection rapidly decreases.
4. Yes.
5. Reversing the current reverses the direction of the force on the coil.
6.



7. Yes--can't tell the difference.
8. Zero.
9. Yes. Needle moves right momentarily.
10. Yes. But in opposite direction.
11. Needle moves to right.
12. Yes, very noticeably.
13. It makes no difference which moves, as long as there is relative motion.
14. Yes--deflection to the right for half a revolution, and to the left for the other half.
15. The meter deflects while the coil is collapsing.
16. The meter deflects momentarily about 1 division.
17. The meter again deflects but in the opposite direction.
18. The meter deflects momentarily to a maximum of about 10 divisions.
19. It is 10 times greater. The presence of iron around the current greatly increases the magnetic effects.

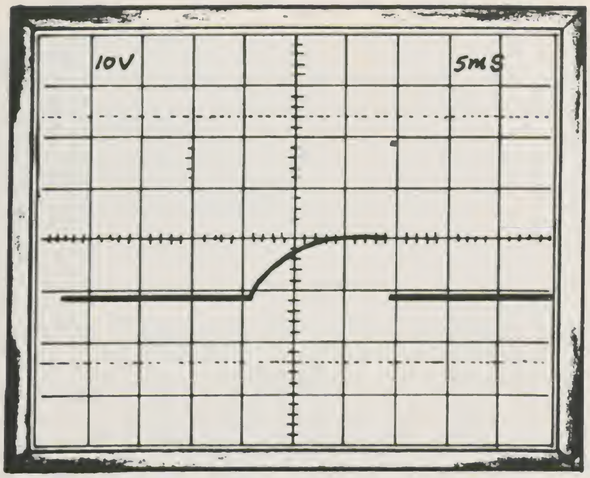
Experiment B-1

1. 0.10 s.
2. $\underline{V}$ = 6.0 V.
3. $\underline{R_B}$ = 1.5 Ω.
4. $\underline{I}$ = 4 A.
5.

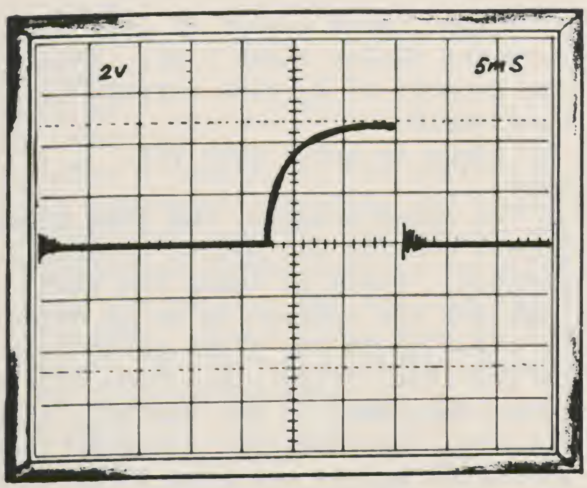


6. The major difference is that the current buildup in the circuit is slower (in about 10 ms, the current is very nearly up to its final value).
7. 6 V.
8. 4 A.
9. About 4 ms.

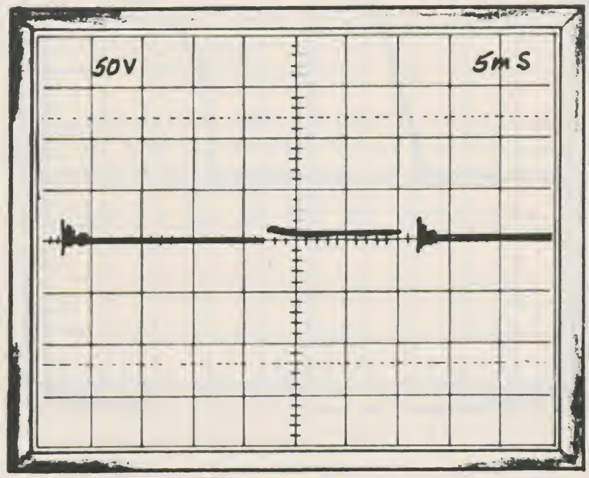
10.



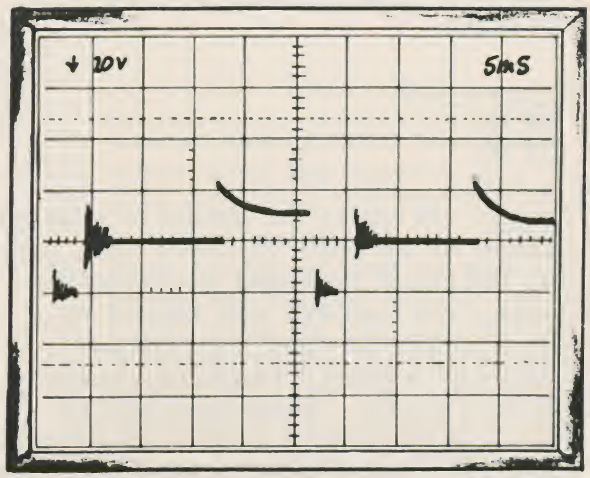
11. It is very different from the RL circuit previously investigated. The current in the circuit drops very slowly to zero. (Note that the center of the Y axis was adjusted carefully to be zero volts before the picture was made.) Another difference is that the current rises abruptly to its maximum, where before the coil prevented rapid buildup of current.
12. About 2.5 milliseconds.
13.



14. The current buildup is low, reminding one of the LR circuit. The current decay is oscillatory--a feature not seen in either the LR or the RC circuit.
15. About 0.6 ms.
16.



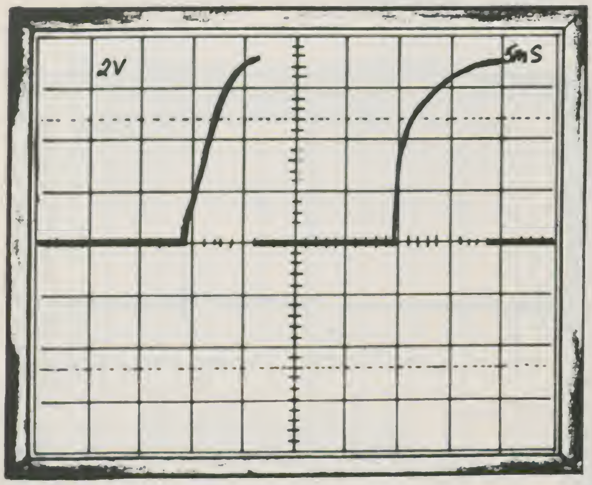
17. About 100 ms.
18.



19. There are three distinct voltage levels as follows:
    1. A negative 5 V around which the oscillation at firing occurs.
    2. A positive 12 V which represents the initial coil voltage when the points first close. (Since there is no current--and hence no resistor drops--this is the battery

voltage.)

20.



21. The pictures are quite similar. Careful examination reveals a second oscillation at a lower frequency occurs after the firing oscillation has died out. This did not happen in the earlier picture.

Experiment B-2

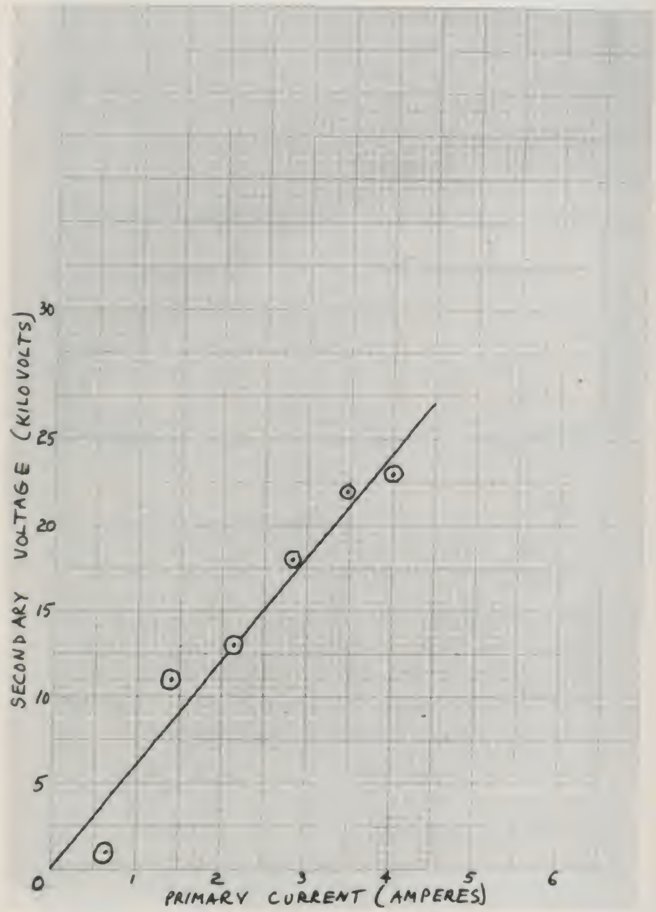
1. 22 kV.
2. 15 kV.
3. 1.5 Ω.

Note: In order to obtain a greater range of primary voltages than can be obtained by speed variation alone, the battery was tapped at each cell, so that any voltage between 0 and 12 could be obtained in 2-V steps. This was done by drilling holes into the connectors, and then using wood screws to bring out a tap.

4,5,6.

$V_{battery}$	V_1	V_s	I_p
12 V	6 V	23kV	4 A
10 V	5.2 V	22kV	3.47 A
8 V	4.2 V	18kV	2.81 A
6 V	3.2 V	13kV	2.13 A
4 V	2.1 V	11kV	1.4 A
2 V	1.0 V	1kV	0.67 A

7. See graph below.



8. It seems linear except at very low currents (below about 1 A). Then the dropoff of V_s with current is very rapid.
9. The slope is about 6000 V/A.
10. Ohms.
11. As the speed changes, the time between points closing and points opening changes. Since it takes the same time for the current in an LR circuit to build up to any given percentage of its final value (this time constant being dependent on the circuit values L and R) irrespective of speed, then at faster speeds the points open before the current has built up to a large percentage of its final value.

Experiment C-1

1. $R_B = 1.5\,\Omega$; $R_P = 1.5\,\Omega$; $R = 3\,\Omega$.
2. $R_r = 10\,\Omega$.
3. $t_d = 10$ ms; $t_f = 2.4$ ms; $t_i = 4.5$ ms.
4. $\tau = 2.6$ ms.
5. $L_P = 7.8$ ms.
6. $T_i = 0.5$ ms.
7. $C_P = 0.8\,\mu$F.
8. τ (firing) = 80 μs; $L_{effective} = 0.2$ mH; $\tau_{decay} = 200$ μs; $L_{effective} =$ 0.3 mH; τ_{decay} (intermediate) = 1 ms; $L_P = 1.5$ mH.
9. $V_i = -8$ V.
10. $\Delta t = 2.4$ ms.
11. $\Delta V = 200$ mV.
12. $\Delta I = 20$ mA.
13. M = 0.96 H.
14. M = 0.71 H.
15. Agreement is quite good.

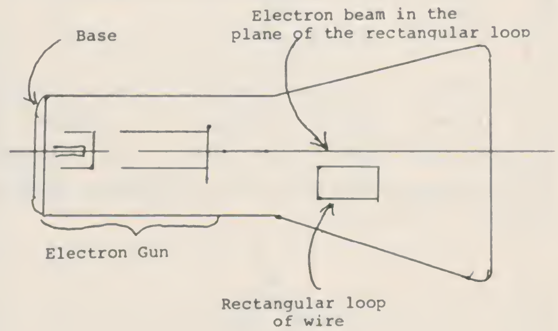
VII SOLUTIONS TO PROBLEMS

1. About 7 ms.
2. 21,400 V.
3. 0.0024 N.
4. 2.8 T.
5. 3 T.
6. 0.4 V.
7. 100 V.
8. 12 V.
9. 1 ms.
10. 40 μF.
11. 0.088 C.
12. After a long time, the current will no longer be changing, and there will be no EMF induced. Hence the only potential differences in the circuit are the battery EMF and the resistor IR drop. Since these must be equal, Ohm's law for the resistor requires the current to be V_b/R.
13. 3.64 A.
14. 13.1 V.
15. Zero, since the current is no longer changing.
16.
17. 40 ms.
18. 0.69 μs.
19. 0.3 ms.
20. 0.166 ms.
21. 2.9 kHz.
22. 0.5 H.

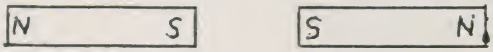
VIII POST-TESTS

Test A-1

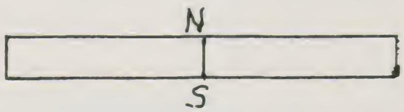
1. When the electron beam is turned on in the modified cathode ray tube shown, will an EMF be induced in the rectangular coil of wire?



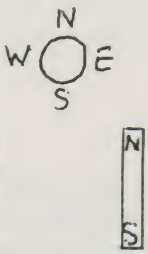
2. The energy that causes the spark at the spark plug gap comes:
   (a) directly from the battery through a complete circuit.
   (b) from energy stored in the capacitor, which has stored energy previously taken from the battery during dwell.
   (c) from the energy stored in the coil's magnetic field, this energy being previously taken from the battery during the dwell period.
   (d) from the energy stored in the ballast resistor as heat.
3. Two bar magnets of equal strength and identical geometry are fastened together to make one magnet, the South poles being placed together as indicated in the figure on the next page. The result will be:



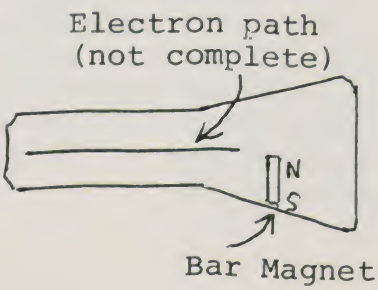
(a) there will be no magnetism left.
(b) there will be North poles on each end, and no South poles at all.
(c) there will be two South poles at the center of the magnet.
(d) the long faces of the magnet will become North and South as shown.



4. Two identical bar magnets are located as shown, and a compass is placed in a central position above the magnets. Will the compass point North, South, East, or West?

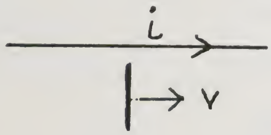


5. A bar magnet is located inside a modified cathode ray tube, as shown in the figure. Draw in the rest of the path of the electron beam if possible; otherwise, explain in words what the path is.

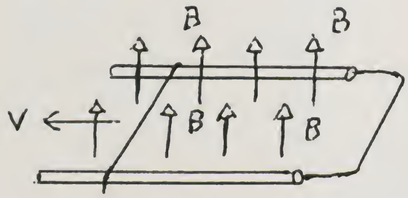


Test A-2

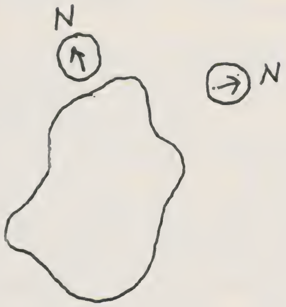
1. (a) A wire is moved with a velocity V in the direction of the current in a nearby wire, as shown in the figure. Will an EMF be induced in the moving wire? (This is a difficult question. If you do not see how to answer it, proceed to the next question.) Explain your answer.

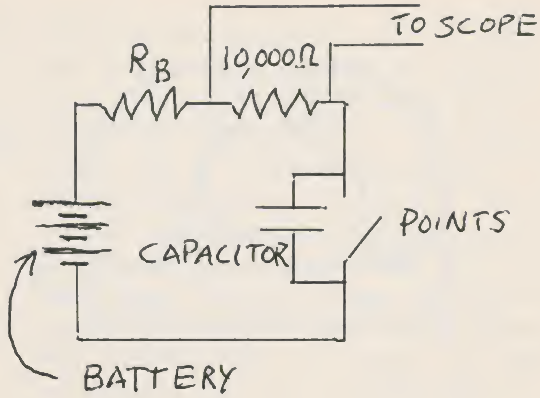


(b) A U-shaped wire lies in a magnetic field as shown. A second wire is given a velocity V in the direction shown. Will an EMF be induced in the wire? Explain your answer.

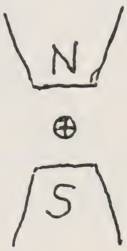


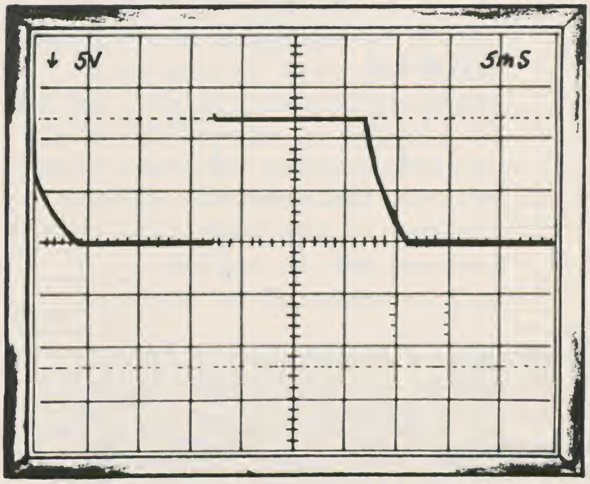
2. What is the function of the breaker points in the ignition system?
3. The so-called North pole of a magnet points in the general direction of Alaska. Does this mean that what we refer to as "the North pole" of the earth" is really a South magnetic pole? Explain.
4. The chunk of material shown on the next page near two small compasses is magnetized. Where is the north magnetic pole?





5. Which way will an electron beam traveling into the page, as shown below, deflect?

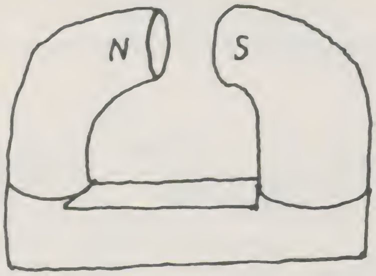




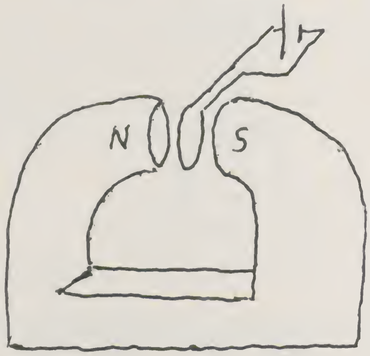
Test B-1

1. The oscilloscope display for the circuit shown has a vertical axis calibration of 5 volts per cm as indicated in the upper left (5 V), and a horizontal time scale of 5 milliseconds per cm as indicated in the upper right (5 ms). The zero for the vertical is at the center of the picture. Determine the time constant associated with the charging of the capacitor. (The centimeter scale will measure other than 1 cm in this reproduction.)

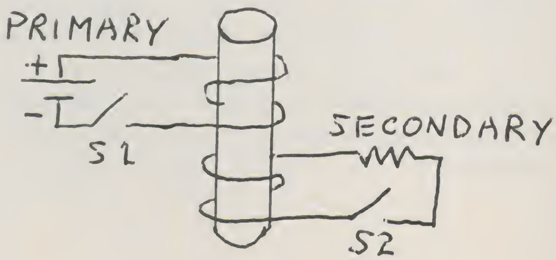
2. A student wishes to determine the strength of a magnet of the type shown on the next page. He uses a No. 6 dry cell (1.5 V) and a clip lead, on which are placed weights, so that they barely lift when the current is turned on. It is found that 40 A will lift 30 g. The poles are 4 cm in diameter, and the gap is 5 cm long. What is the approximate strength of the magnetic field?



3. Complete the following statements:
   (a) When the current in a coil changes, the magnetic field caused by that current changes. Since the coil is now in a changing magnetic field, an EMF is induced in the coil. The proportionality constant that relates the rate the current changes to the magnitude of the induced EMF is called ______ and is measured in units of ______.
   (b) When a capacitor is charged, plus and minus charge are separated by a gap (sometimes air, sometimes some other insulation). When a voltmeter is connected across the capacitor a certain voltage is read. If an identical capacitor is now connected so that it has half the charge and the original capacitor has the other half of the charge, the voltage is found to be half as much. This proves that charge is proportional to voltage. The proportionality constant is called ______and is measured in units of ______.
   (c) If the magnetic field caused by a current in a coil links the turns of another nearby coil, then a change in current in the first coil will induce an EMF in the second coil. The proportionality constant that relates the rate of change of current in the first coil to the EMF induced in the nearby coil is called ______and is measured in units of ______.
   (d) In Problem 2 above, I found the magnetic field strength was ______. Therefore the total magnetic flux was ______(give units).
4. A single coil of wire is inserted into the magnetic field of the magnet shown in the figure for Problem 2. The diameter of the coil is the same as the pole diameter. How much time could elapse while pulling the coil out of the magnetic field, if there is to be zero current in the wire during this time? (The battery EMF is 1.5 V.)



5. Cross out all but the correct answers within the parentheses in the following statements.



When switch 1 is closed with switch 2 open, positive charge would move (up, down) through the battery. The increasing current would cause a changing magnetic field, and this

in turn would induce an EMF in the primary coil that would tend to make positive charge move (up, down) through the battery.

When switch 2 is first closed, and then switch 1 is closed, the changing magnetic field caused by the increasing primary current also induces an EMF in the secondary coil which makes positive charge move (left, right) through the resistor. This secondary current also has an associated magnetic field that tends to (strengthen, weaken, not change) the total magnetic field, which is now due to both primary and secondary currents. The effect of current in the secondary on the primary current is to cause (more, less, the same) primary current to flow than was present with the secondary open. The induced EMF in the primary with the secondary conducting is (more than, less than, the same as) it was with the secondary open.

Test B-2

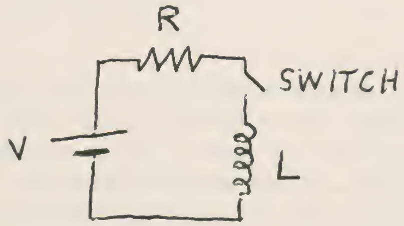
1. The scope trace shown below shows the voltage across a ballast resistor of an ignition system as the points open and close with the capacitor and secondary circuit disconnected. What is the time constant of the circuit?

2. A 10-cm wire carrying a current of 2 A at right angles to a magnetic field experiences a force of 0.5 N. What is the magnitude of the magnetic field?

3. What is the capacitance of a capacitor that stores 3×10^{-6} C at a potential difference of 120 V?

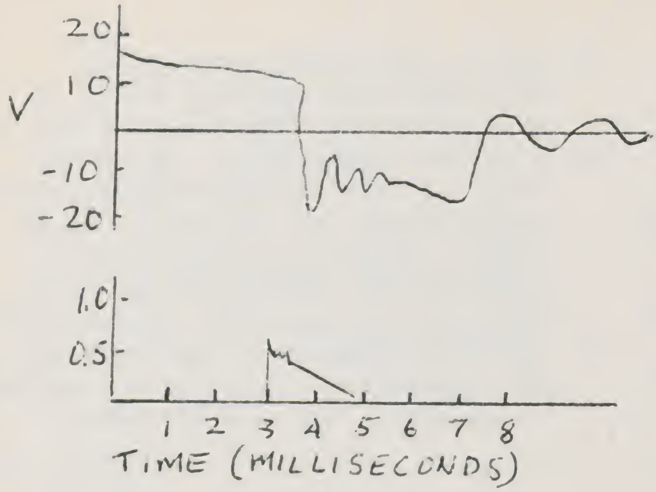
4. A 10-turn square coil, 20 cm on a side, is in a uniform magnetic field perpendicular to the coil. It is jerked out of the field in 0.8 s, producing an induced EMF of 12 V. What was the magnitude of the field?

5. Show the polarity of the induced EMF across the coil when the switch is closed in the circuit below.

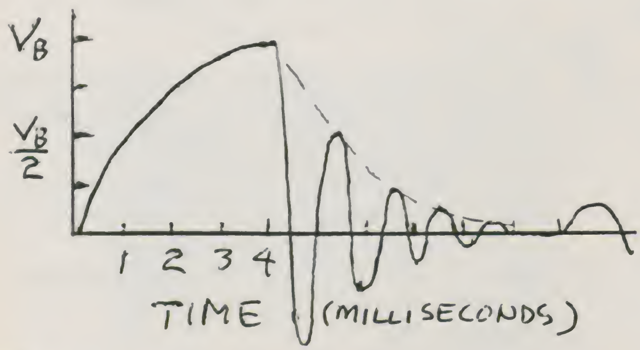


Test C-1

1. An initially charged capacitor with 0.5-μF capacitance is connected in series to a 6-Ω resistance and 3-mH inductance. How long does it take the capacitor to discharge to 36.8% of its initial charge?
2. What is the period of oscillation of the circuit described in Problem 1?
3. A 10-mH coil is wound on an iron core. What must be the self-inductance of a second coil wound on the same core, in order to produce a mutual inductance between the two of 0.08 H?
4. The scope traces shown on the next page show the voltages across the primary coil and across a 20-Ω resistor between the low-voltage end of the spark gap and ground, respectively. What is the mutual inductance between the primary and secondary coils?

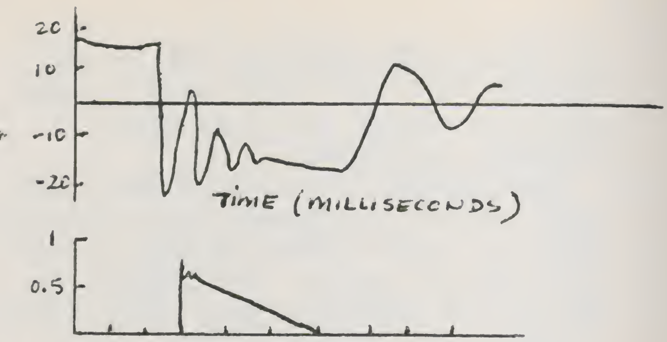


5. The scope trace below is the voltage across the primary circuit of an ignition system. With a resistance of 6 Ω, find the "effective" inductance of the primary coil while the secondary circuit is conducting.

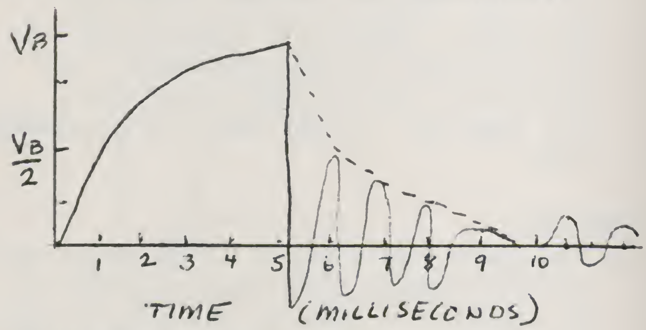


Test C-2

1. The switch on a circuit containing a 6-V battery in series with a 3-Ω resistor and 10-mH inductance is closed. How long does it take for the current to build up to 1.26A?
2. If you wish to build an oscillating circuit with a period of 10^{-6} s, what capacitance should you use with a 2-mH inductance?
3. The scope traces shown show the voltages across the primary coil and across a 15-Ω resistor between the low-voltage end of the spark gap and ground, respectively, What is the mutual inductance between the primary and secondary coils?



4. If the primary coil in the problem above has a self-inductance of 3 mH, what is the self-inductance of the secondary coil?
5. The scope trace below is the voltage across the ballast resistor of an ignition system. With a resistance of 3 Ω, find the "effective" inductance of the primary coil while the secondary circuit is conducting.



SOLUTIONS TO POST-TESTS

Test A-1

1. The flux in the loop will be out from the page. Flux from coil current will be into the page by Lenz's law. Hence conventional current in the coil will be clockwise.
2. (c)
3. (c)
4. Because of the symmetry, there is no reason to prefer East over West. Hence the compass will point North.
5. The force will be into the page, and hence the electron beam will be deflected into the page and cannot be shown on the picture.

Test A-2

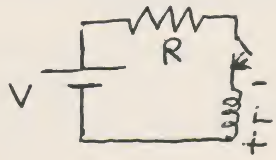
1. (a) (This question requires some inventiveness on the part of the student and is difficult for most

students; it is included because it gives a good problem for after-test discussion.) We imagine the current-carrying wire is short, and the wire we are moving is part of a longer coil. Let us put the coil off to the left as shown in the figure below. (We could put the coil to the right if we preferred--we would get the same answer.) Since the total flux through our coil is increasing, with the direction into the page, any current that circulates due to induced EMF's will be out of the page, resulting in a counter-clockwise circulation in the imagined coil. This makes the EMF in the original wire upward, and the farthermost end is positive.

(b) Since the flux is increasing in the loop, in the upward direction, Lenz's law requires that the flux due to any current flowing in the loop be in the downward direction so as to oppose the change in flux. To get the downward flux, current will have to circulate clockwise, as viewed in this picture. (It will be noted that the force on the wire will be a stopping force, and hence work is being done to keep the wire moving.)

2. To interrupt the current in the primary circuit and produce a collapsing magnetic field in the coil.

3. The earth's geographic (or rotational) North pole is in the Alaskan region, but the earth's South magnetic pole is in this region.
4.



Roughly at the intersection of the lines as shown.
5. To the right.

Test B-1
1. 2.5 ms.
2. 0.184 T.
3. (a) Self-inductance (L), henrys; (b) capacitance, farads; (c) mutual inductance, henrys; (d) 0.184 T, 0.023 Wb.
4. 15.3 ms.
5. When switch 1 is closed with switch 2 open, positive charge would move up through the battery. The increasing current would cause a changing magnetic field, and this in turn would induce an EMF in the primary coil that would tend to make positive charge move down through the battery.

When switch 2 is first closed, and then switch 1 is closed, the changing magnetic field caused by the increasing primary current also induces an EMF in the secondary coil which makes positive charge move left through the resistor. This secondary current also has an associated magnetic field that tends to weaken the total magnetic magnetic field, which is now due to both primary and secondary currents. The effect of current in the secondary on the primary current is to cause more primary current to flow than was present with the secondary open. The induced EMF in the primary with the secondary conducting is the same as it was with the secondary open.

Test B-2

1. About 0.4 ms.
2. 2.5 T.
3. 0.025 μF.
4. 24 T.
5. Opposing the battery.

Test C-1

1. 10^{-3} s.
2. 2.4×10^{-4} s.
3. 0.64 H.
4. 0.8 H.
5. 4.5 mH.

Test C-2

1. 3.33 ms.
2. 12.7 pF.
3. 0.75 H.
4. 187 H.
5. 4.5 mH.

IX LIST OF APPARATUS

Experiment A-1

Automobile ignition system with motor drive
12-V battery and leads

While Physics of Technology equipment may be purchased from Thornton Associates, some teachers may wish to assemble their own apparatus. The following notes are added as helpful information for such teachers.

To drive the distributor, an electric drill motor works very well. These motors are variable speed, and have ample torque even for the smallest 1/4-inch home model. Used with a Variac, the speed range is from very slow up to 2400 rpm, which matches automobile engine speeds closely enough for this module.

Some companies have a horizontal drill stand for some models of their drills (e.g., Black and Decker model U2308). (Later models of Black and Decker drills have the case screws in the back instead of the front, so that one must take care to get a drill that will fit the stand.)

Some companies are marketing horizontal drill stands for the "99¢" tool stands. These are suitable for both the drill and the distributor. Shimming, using for example floor tiles, may be necessary to obtain good alignment, (Poor alignment leads to unsteady speeds, very noticeable at low speeds.)

A base made of 1/2- or 3/4-inch plywood, about 12 x 24 inches, is adequate space for mounting all the components. Care must be taken to get good ground connections between the distributor and the negative side of the battery.

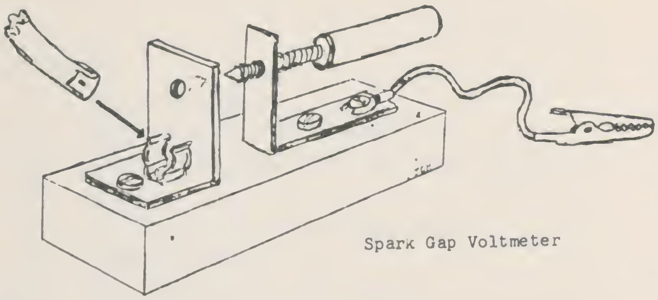
The ignition system components are quite expensive if purchased new. For example, typical prices are \$13.50 for a coil, \$33.50 for a distributor (or \$27.40 rebuilt), \$2.50 for the ballast resistor, \$3.50 for wiring, and from \$4.00 to \$8.00 for plugs. In addition, an automobile battery is needed. (Power supplies will have more resistance, and since the primary circuit resistance is only 3 Ω, this extra resistance prevents the circuits from normal operation.) A new battery may cost \$20.00, giving a total of more than \$60.00 for one set-up, not counting the drill and its mounting.

One automobile junk yard in St. Louis quotes the following prices for used distributors which have been cleaned up:

Coil and distributor (matched set), wiring, and used spark plugs, but without ballast resistor, \$20.00.
Battery, 12-V, used but guarantee operational, \$10.00.
Ballast resistor, new, \$2.50.

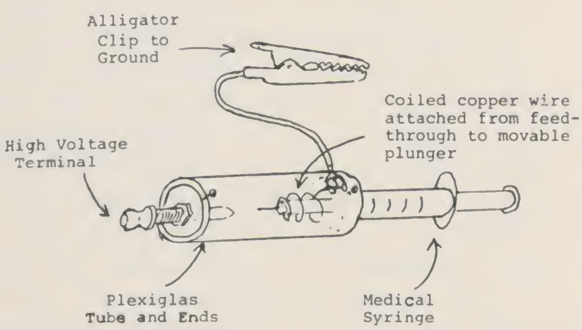
If a home model drill is used (\$8.95), the cost of a set-up is about \$45.00.

The high-voltage spark gap voltmeter may be constructed in several ways. Two methods are shown in figures on the following page.



Spark Gap Voltmeter

The spark gap meter below is constructed with a 1-inch-diameter Plexiglas tube and a medical syringe. A straight pin is cemented to the movable plunger of the syringe and a coiled copper wire is attached from the feedthrough to the pin and soldered at the base of the pin. The syringe cylinder may be calibrated in centimeters or in volts if the conversion in the module is used.



<u>Experiment A-2</u>
Rod magnet (3)
Paper clips (5 to 10)
Magnetic compass
Glass or plastic sheet
Iron filings (several grams)
Cathode ray tube
  (such as a demonstration oscilloscope)
Coil of wire (2)
  (such as a Gilly Induction Coil)
DC variable power supply (0 to 5 A)
Electrical connecting leads
Cardboard sheet (for sprinkling iron
  filings around Gilly Coil)
Galvanometer
Collapsible coil (wire wound on a
  collapsible open-ended small card-
  board box)
U-shaped iron core (for Gilly Coils)

<u>Experiment B-1</u>
Automobile ignition system with motor
  drive
12-V automobile battery
Ballast resistor (in addition to the one
  in the ignition system)
Oscilloscope
Ohmmeter
10,000-Ω resistor

<u>Experiment B-2</u>
Automobile ignition system with motor
  drive, battery, and electrical leads
Spark-gap voltmeter
Oscilloscope
Ohmmeter

<u>Experiment C-1</u>
Automobile ignition system with motor
  drive, battery, and electrical leads
Spark-gap voltmeter
Oscilloscope
10-Ω 5-W resistor

OPTIONAL DEMONSTRATION AIDS

<u>16-mm Sound Film</u>
"Introduction to the Cathode Ray Oscilloscope." Encyclopedia Britannica Educational Corp.

<u>8-mm Film Loops</u>
1. "Ignition Timing Adjustment." Eothen Films Limited.
2. "Timing an Engine."
3. "Adjusting the Distributor Cam Angle."
4. "Replacing Ignition Points." Modern Learnii Aids.
5. "The RC Time Constant--Long and Short."
6. "The Undamped Oscillation."
7. "The Damped Oscillation."
8. "Series RL Circuits."
9. "Series RC Circuits."
10. "Series RLC Circuits." Animated Electronic Films.
11. "Lead-Acid Storage Battery."
12. "Resistance."
13. "Ohm's Law."

14. "Magnetism Produces Electricity." International Communication Films.
15. "Electro-Magnetic Induction."
16. "Mutual Induction." Macmillan & Co., Ltd.

Overhead Transparencies

1. "R-C Circuits," EM4.
2. "Oscillating L-C Circuits," EM9. John Wiley & Sons, Inc.
3. "Magnetic Lines of Force," No. Z-8662-045.
4. "Magnetic Field," No. Z-8662-047. LaPine Scientific Co.
5. "An EMF Induced by Change of Flux," No. 6905.
6. "Induced Current Always Produces Opposing Magnetic Force," No. 6907.
7. "An EMF Is Produced Only by a Change in Flux," No. 6910. Frey Scientific Co.

CONTENTS

I INTRODUCTION

The Binoculars module has been designed to follow the Camera module. The Binoculars module emphasizes: real and virtual image formation by a lens system; changes in the diameter of the pupil of the eye to accommodate changing amounts of light; optical specifications for various binoculars; focal lengths of converging and diverging lenses; and principal planes and principal ray diagrams for converging and diverging lenses.

The principles treated include: the law of reflection for a plane surface; the law of refraction (Snell's law); index of refraction and dispersion in a prism; angular magnification of a telescope; and total internal reflection.

II SPECIAL PREREQUISITES

Special prerequisites are the skills and concepts taught in the Camera module: the production of an image by a lens, the definition of focal length, object and image distance, and the lens equations: $\underline{xx}' = \underline{f}^2$ and $\underline{H}_i/\underline{H}_o = \underline{f}/\underline{x}$.

III TABLE OF CONTENTS OF THE MODULE

Experiment C-2. Dependence of Magnification of a Monocular on Pupil Diameters
Porro Prisms
Condition for Total Internal Reflection
Buying Binoculars
Appendix (Trig Function Table)
Work Sheets

IV GOALS

The goals of the Binoculars module have been included at the beginning of each section of the module.

V DISCUSSION OF ACTIVITIES

The module is divided into three parts, each representing one week's study.

SECTION A

The first section is largely qualitative. The student is introduced to the binoculars in the lab, and he makes several observations which raise questions for which answers are not yet provided. The section concludes with a discussion of the binocular specifications and the principles which explain some of the students' observations, and a summary of the qualitative principles and concepts he has learned. During this first week, the teacher may also want to conduct classroom demonstrations.

First Class Period

1. Show and explain monoculars or binoculars with various specifications (e.g., 7 x 35) and a telescope.
2. Do experiment A-1 as a classroom demonstration if it cannot be done as a lab very early in the week.

Experiment A-1. The Monocular

The purposes of this experiment are: to familiarize the student with the monocular (or binoculars) and the image formed by it; and to relate monocular specifications (e.g., 7 x 35) to measurable quantities in the instrument.

This experiment is designed to raise questions about the physics of the monocular. Most of these questions are answered through observations or descriptively in the module, and most of the quantitative and analytical material of the module is based on the qualitative observations students make in this experiment.

Second Class Period

1. Discuss some of the steps and questions of Experiment A-1. Ask about results students are getting and how these results should be interpreted.
2. Discuss Experiment A-2 in terms of what is to be done and how data are analyzed.

Experiment A-2. Monocular Components

The purposes of this experiment are: to measure the focal lengths of two converging lenses that form a simple telescope; to determine the optimum distance between the lenses of a simple telescope to obtain a sharp image when viewing through it; and to insert a prism system between the lenses of a simple telescope and determine its effect on the viewed image.

Third Class Period

1. The results of Experiment A-2 should be discussed.
2. Discuss Question 4 and Problem 1.
3. Discuss binocular standard specifications and Problems 2, 3, and 4.
4. Discuss those Section A goals and sample items for which the students need further explanation.
5. Administer Section A post-test (5 items, 25 minutes).

SECTION B

The second section of the module has the student arrive empirically (in the lab) at the law of reflection at a plane surface and the law of refraction (Snell's law). The empirical equations are discussed quantitatively, with

appropriate problems and exercises. The method of determining image formation in converging and diverging lenses by means of principal ray diagrams is introduced. The section concludes with applications of lens principles to the binoculars and other devices. Experiment B-1 should be completed very early in the week. Experiment B-2 may be completed later in the week. If time doesn't permit both experiments to be completed by the student, Experiment B-1 may be done as a demonstration in class.

The teacher may want to do the following activities in this second week of study:

First Class Period

1. Discuss Experiment B-1 in terms of what is to be done and how data are analyzed (or it may be done as a classroom demonstration).
2. Show film, "Lenses" (15 minutes).

Experiment B-1. Reflection and Refraction

The purposes of this experiment are: to observe the conditions and principles of reflection and refraction of light at a material boundary; to discover the law of reflection; and to discover the law of refraction (Snell's law).

Second Class Period

1. Discuss the results of Experiment B-1.
2. Discuss Problems 5, 6, and 7.
3. Discuss lens equations, $xx' = f^2$ and $H_i/H_o = f/x$.
4. Discuss thin and compound lenses.
5. Discuss Experiment B-2 in terms of what is to be done and how data are to be analyzed.

Experiment B-2. Diverging Lenses

The purposes of this experiment are: to observe and locate the virtual image produced by a diverging lens; to determine the focal length for a diverging lens, where no real image can be found, by direct measurements of image height and angular size of the object ($f = H_i/\alpha$); and to verify the lens equation, $xx' = f^2$, for a diverging lens.

Third Class Period

1. Discuss results of Experiment B-2.
2. Discuss principal ray diagrams.
3. Administer Section B post-test (5 items, 25 minutes).

SECTION C

Section C is a theoretical and analytical section. It derives magnification in terms of focal lengths as well as in terms of entrance and exit pupil diameters. The student performs a laboratory verification of the magnification relationship. The section is concluded with a derivation of the total internal reflection equation and a short discussion of how the principles and concepts learned in the module may be applied to the purchasing of binoculars.

The student should do Experiment C-1 early in the week and Experiment C-2 later in the week.

Class time might be devoted to the following activities.

First Class Period

1. Discuss angular magnification.
2. Discuss Problem 10.
3. Discuss Experiment C-1 in terms of what is to be done and how data are to be analyzed.

Experiment C-1. Angular Magnification and Focal Lengths

The purposes of this experiment are: to determine experimentally the angular magnification of several telescopes, all with the same focal length eyepiece but different focal length objective lenses; to estimate the uncertainties in the measured magnifications; and to graphically compare these measured values to those predicted from f_o/f_e.

Second Class Period

1. Discuss the results of Experiment C-1
2. Discuss Problems 11 and 12.
3. Discuss Experiment C-2 in terms of what is to be done and how data are to be analyzed.

Experiment C-2. Dependence of Magnification of a Monocular on Pupil Diameter

The purposes of this experiment are: to measure exit pupil diameters for various entrance pupil diameters of a monocular; and to compute the magnification from the average value of the ratios of entrance pupil diameter to exit pupil diameter.

Third Class Period

1. Discuss total internal reflection.
2. Discuss Problems 14, 15, and 16.
3. Administer the post-test for Section C (5 items, 25 minutes).

VI SAMPLE DATA

Experiment A-1

1. The scene is enlarged and right side up.
2. The scene is smaller than without the monocular, but it is right side up.
3. The scene gets dimmer.
4. No.
5. No.
6. Because there is no real image of the scene found outside the monocular.
7. A dark area in the shape of the pencil point appears in the corresponding place on the circle of light. The circle of light is an image of the objective lens opening.
8. 7 x 35.
9. 1-1/2 inches, 3.6 centimeters, 36 millimeters.
10. Yes. The millimeter diameter of the lens is close to the second number in the specifications.
11. The larger the diameter, the brighter the image.
12. 7.
13. Yes. It corresponds to the first number in the specifications.

Experiment A-2

1. f_1 = 20 cm; f_2 = 5 cm.
2. Distance = 25 cm.
3. This distance is equal to the sum of the focal lengths.
4. Lens 1 for the objective and lens 2 for the eyepiece.
5. The image formed is a magnified and inverted image of the scene.
6. Magnification is about 4.
7. Lens 2 is the objective and lens 1 is the eyepiece.
8. The image formed is smaller than the view without the lenses and inverted.
9. The magnification is about 1/4.
10. An image of the objective lens may be formed but no image of the distant scene.
11. 20 cm.
12. The distance is equal to the focal length of the objective lens.
13. The image formed is a magnified upright image of the scene.
14. The image is right side up with the prism system and upside down without the prism system.
15. 19 cm.
16. It is 6 cm less with the prism system than without it.

Experiment B-1

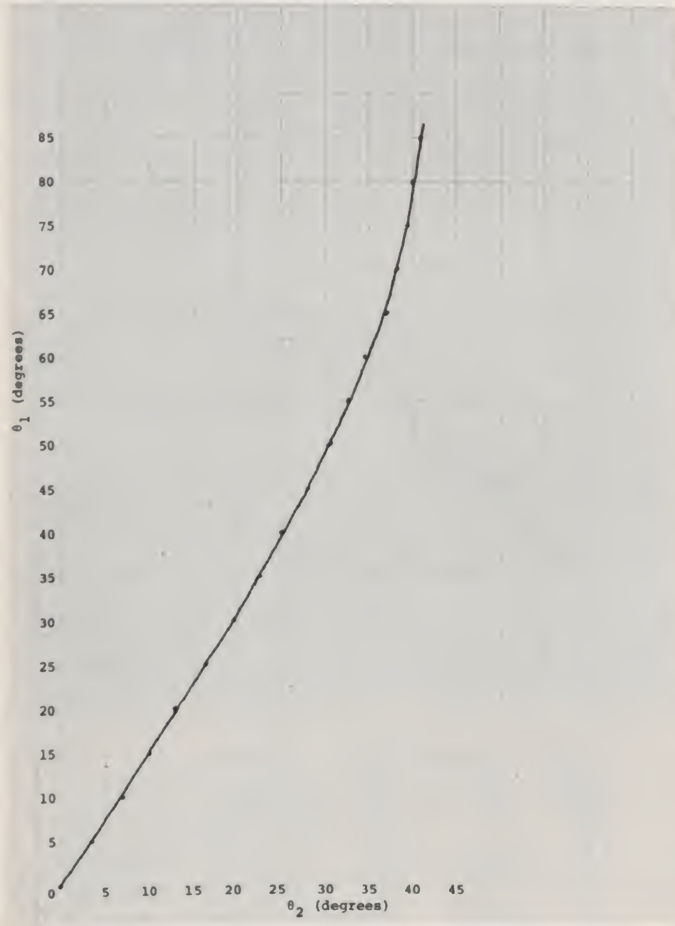
1.

θ_1	θ_r	θ_2
0°	0°	0°
5°	5°	3.5°
10°	10°	7°
15°	15°	10°
20°	20°	13°
25°	25°	16.5°
30°	30°	19.5°
35°	35°	22.5°
40°	40°	25°
45°	45°	28°
50°	50°	30.5°
55°	55°	32.5°
60°	60°	34.5°
65°	65°	37°

70°	70°	38°
75°	75°	39.5°
80°	80°	40°
85°	85°	41°

$\theta_{\underline{r}}$ equals θ_1.

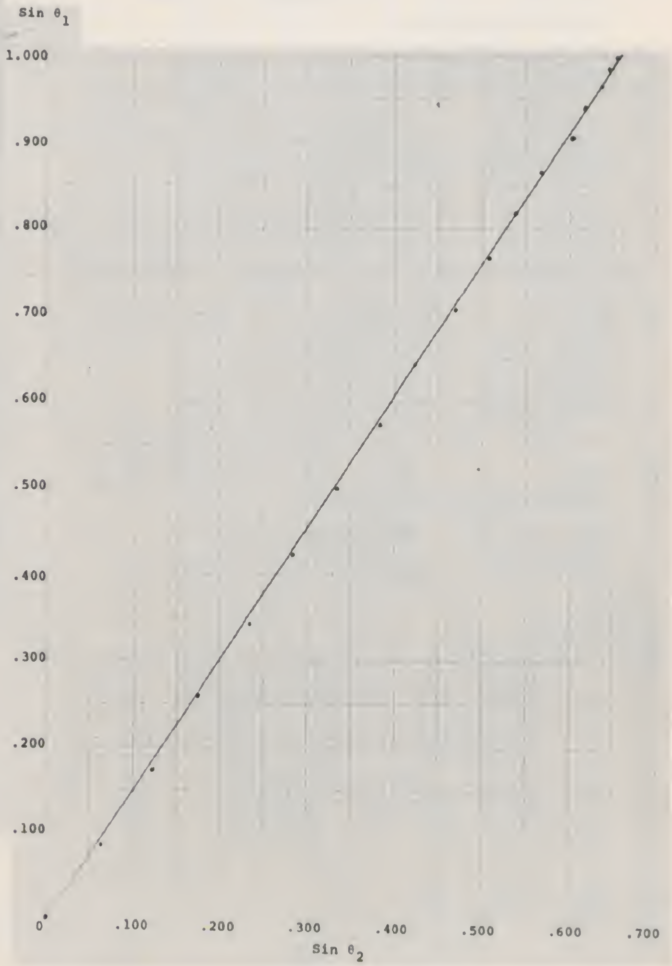
2. As θ_1 gets bigger, θ_2 gets bigger.
3. No. (See graph below.)



4.

Sin θ_1	Sin θ_2
0.00	0.000
0.087	0.063
0.174	0.122
0.259	0.174
0.342	0.225
0.423	0.284
0.500	0.334
0.574	0.383
0.643	0.423
0.707	0.470
0.766	0.508
0.819	0.538
0.866	0.567
0.906	0.602
0.940	0.616
0.966	0.636
0.985	0.643
0.996	0.656

5. Yes. (See graph below.)



6. Slope = 1.52.
7. Sin θ_1 = 1.52 sin θ_2, <u>or</u>

$$\frac{\sin \theta_1}{\sin \theta_1} = 1.52.$$

8. From this point on no refraction occurs. Only reflection takes place inside the glass.
9. Yes. The intensity increases.
10. The part of the light ray that was refracted is now reflected internally.

<u>Experiment B-2</u>

1. Position of lens = 50 cm.
2. Position of one focal plane = 29.5 cm.
3. Position of other focal plane = 71.0 cm.
4. Angular size of distant object = 0.065 radians.
5. $\underline{H_i}$ = 1.37 cm.
6. $\underline{f}$ = 21.2 cm.
7.

Object position	Image position
30.5 cm	40.5 cm
25.5 cm	39.0 cm
20.5 cm	37.0 cm

8.

x	x'
40.5 cm	11.0 cm
45.5 cm	9.5 cm
50.5 cm	8.0 cm

9.

xx'	f^2
445.5 cm^2	450 cm^2
432.3 cm^2	450 cm^2
404.0 cm^2	450 cm^2

<u>Experiment C-1</u>

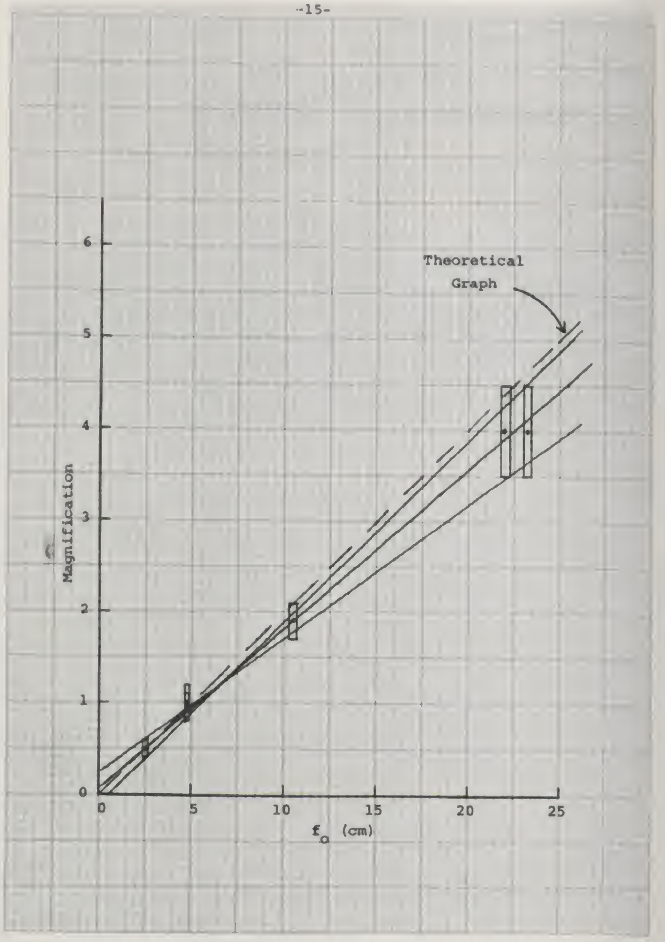
1.

	f_o	f_o
A	23.2 cm	0.2 cm
B	10.5 cm	0.2 cm
C	4.8 cm	0.1 cm
D	2.5 cm	0.1 cm
E	22.0 cm	0.3 cm

2. $\underline{f_e}$ = 5.0 cm.
3.

f_o	M
23.2 cm	4.7
10.5 cm	2.1
4.8 cm	0.96
22.0 cm	4.4

4. See graph below.



5.

Lens	M	ΔM	f_o	Δf_o
A	4	0.5	23.2 cm	0.2 cm
B	1.9	0.2	10.5 cm	0.2 cm
C	1	0.2	4.8 cm	0.1 cm
D	0.5	0.1	2.5 cm	0.1 cm
E	4	0.5	22.0 cm	0.3 cm

6. Slope of experimental line = 0.175/cm.
   Maximum slope = 0.196/cm.
   Minimum slope = 0.146/cm.
   Slope = 0.174/cm ± 0.025/cm.
7. $\underline{f_e}$ = 5.7 ± 1.7 cm.
   The theoretical value falls between the limits of the experimental values, and so the equation $\underline{M} = \underline{f_o}/\underline{f_e}$ adequately predicts the magnification.

Experiment C-2

1. M = 7.
2.

D(cm)	ΔD	d(cm)	Δd
0.5 cm	0.03 cm	0.08 cm	0.01 cm
1.5 cm	0.03 cm	0.24 cm	0.01 cm
2.0 cm	0.03 cm	0.28 cm	0.01 cm
2.5 cm	0.03 cm	0.36 cm	0.01 cm
3.0 cm	0.03 cm	0.42 cm	0.01 cm

3.

M	$\Delta D/D$ x 100	$\Delta d/d$ x 100	Sum
6.25	6%	12.5%	18.5%
6.25	2%	4.1%	6.1%
7.14	1.5%	3.6%	5.1%
6.94	1.2%	2.8%	4.0%
7.05	1.0%	2.4%	3.4%

4. Average M = 6.7.
   Average error = 7%.
   Error estimate in M = 0.5.
   $M = 6.7 \pm 0.5$.

VII SOLUTIONS TO PROBLEMS

The problems and questions are an important part of the module and should be discussed in class. The problem answers are provided below.

1. $$\frac{A_2}{A_1} = \frac{D_2^{\,2}}{D_1^{\,2}} = \frac{50^2}{35^2} = 2$$

   Twice as much light enters the 7 x 50 monocular as enters the 7 x 35.
2. Magnification = 8, objective diameter = 35 mm.
   Exit pupil diameter = 35 mm/8 = 4.4 mm.
3. $\frac{50 \text{ mm}}{8} = 6.25$ mm

   $$A = \frac{\pi}{4} d^2 = \frac{3.14 \times (6.25 \text{ mm})^2}{4}$$

   Exit pupil area A = 30.7 mm^2
   Eye pupil area $A = 3.14(5 \text{ mm})^2/4$ = 19.6 mm^2
   Proportion of light entering eye

   $$= \frac{19.6 \text{ mm}^2}{30.7 \text{ mm}^2} = 0.64$$
4. $$d = \frac{35 \text{ mm}}{7} = 5 \text{ mm}$$

   $$\text{Proportion} = \frac{(2.5 \text{ mm})^2}{(5 \text{ mm})^2} = 1/4 = 0.25$$
5. $$n = \frac{\sin 46°}{\sin 26°} = \frac{0.72}{0.44} = 1.64$$
6. $$\sin\theta = \frac{1.36 \sin 37°}{1.63} = \frac{1.36(0.6)}{1.63}$$

   $$= 0.5.$$
   $$\theta = 30°$$
7. $x' = f^2/x = 16 \text{ cm}^2/5 \text{ cm} = 3.2$ cm.
   $H_i = H_o f/x = 1 \text{ cm}(4 \text{ cm})/5 \text{ cm} = 0.8$ cm.
8. An inverted image of height 1.5 cm is located 2.5 cm away from the image focal point.
9. An erect virtual image of height 1 cm is located 1.7 cm toward the lens from the image focal point.
10. (a) The 50-cm focal length lens would be the objective and the 2-cm lens the eyepiece.
    (b) The image is at the image focal point.
    (c) For a distant object the distance between lenses is for all practical purposes just the sum of the two focal lengths, 52 cm.
11. $M = f_o/f_e = 300 \text{ cm}/10 \text{ cm} = 30$
    $d = D/M = 6 \text{ cm}/30 = 0.2$ cm
12. $d = D/M = 5 \text{ cm}/8 = 0.63$ cm
13. $d_1 = 35 \text{ mm}/7 = 5$ mm
    $d_2 = 40 \text{ mm}/10 = 4$ mm
    $B_1/B_2 = d_1^{\,2}/d_2^{\,2}$

    $B_1/B_2 = (5 \text{ mm})^2/(4 \text{ mm})^2$
    $B_1/B_2 = 25/16 = 1.6$
    The image is 1.6 times brighter.
14. $\sin\theta_c = 1/2.4 = 0.417$

    $\theta_c \cong 24.5°$
15. $n = 1/\sin 49° = 1/0.755 = 1.33$
16. Diamond has a higher index of

refraction and a lower critical angle than glass.

VIII POST-TESTS

Test A-1

1. Suppose that you are looking at some scene through a monocular and that the right half of the objective lens of that monocular is covered by some object. Choose the statement below which best describes what you would see.
   (a) The right half of the image would not be visible.
   (b) The whole image would be visible but only half as bright as it would be without the lens half covered.
   (c) The left half of the image would not be visible.
   (d) The right half of the image would be half as bright as the left half.
2. What are the main parts of a simple telescope, and what does each part do?
3. Is the image formed in a camera a real or a virtual image? Explain your answer.
4. Using a monocular or binoculars on which the specifications have been concealed, use the even spaces indicated by your instructor to determine the magnification of the instrument. You should be able to do this within three minutes.
5. Two monoculars are used to view the same object. One is a 7 x 35 monocular and the other is a 6 x 50 monocular. Which monocular has the most light in its exit pupil? How much more light is there in this exit pupil than in that of the other monocular?

Test A-2

1. Suppose that you are looking at some scene through a monocular and that a coin whose diameter is one-half that of the objective lens is taped over the center of the objective lens. Choose the statement below which best describes what you would see.
   (a) The center of the image would not be visible.
   (b) The whole image would be visible but only half as bright as it would be if the lens were not covered by the coin.
   (c) The whole image would be visible but only three-fourths as bright as it would be if the lens were not covered by the coin.
   (d) The center of the image would be dimmer than the rest of the image.
2. What are the main parts of a monocular, and what does each part do?
3. Is the image formed in a camera a real or a virtual image? Explain your answer.
4. Using a lab telescope, use the even spaces indicated by your instructor to determine the magnification of the instrument. You should be able to do this within three minutes.
5. Two monoculars are used to view the same object. One is an 8 x 40 monocular and the other is an 8 x 50 monocular. Which monocular has the most light in its exit pupil? How much more light is there in this exit pupil than in that of the other monocular?

Test B-1

(A centimeter ruler should be supplied with this test and the student should be instructed to use a full 8-1/2 x 11 sheet of paper for principal ray diagrams. The back of a page of the test would do nicely.)

1. A cylindrical water glass is filled to the brim with water and has a light ray strike the surface of the water in the center of the glass at an angle of 20° from the normal. If the glass is 15 cm high and has a diameter of 7 cm, will the light ray strike the side of the glass before striking the bottom? n = 1.33 for

water.

2. Recalling the definition of principal points, principal planes, and focal points, which of the following statements best describe the relationship between these quantities and the axis and the surface of a compound lens system?
   (a) The focal points and principal points must lie on the axis and the principal planes must be perpendicular to the axis and lie inside the compound lens.
   (b) The focal points and the principal points must lie on the axis and the principal planes must intersect the axis at equal distances from the lens surfaces.
   (c) The focal points and the principal points must lie on the axis and the principal points must be at equal distances from the focal points.
   (d) The focal points and the principal points must lie on the axis and the principal planes must lie outside the compound lens.
3. For a converging lens of focal length 10 cm, an object is placed 5 cm outside the focal point. The object is 3 cm high and the principal planes are 2 cm apart.
   (a) Construct a principal ray diagram and locate the image.
   (b) From the diagram, determine the image height and the image distance.
4. For a diverging lens of focal length 10 cm, an object is placed so that the object distance is 3 cm high and the principal planes are 1 cm apart.
   (a) Construct a principal ray diagram and locate the image.
   (b) From the diagram, determine the image height and the image distance.
5. A ray of white light is incident on the boundary of glass and air, from the inside of the glass. The angle of incidence is precisely the critical angle for red light. Describe what happens to the red part and the blue part of the incident ray.

<u>Test B-2</u>

(A centimeter ruler should be supplied with this test and the student should be instructed to use a full 8-1/2 x 11 sheet of paper for principal ray diagrams. The back of a page of the test would do nicely.)

1. A cylindrical block of plastic (n = 1.38) standing on the circular end has a light ray strike the center of the top circular surface at an angle of 20° from the normal. If the cylinder is 15 cm high and has 6-cm-diameter circular ends, will the light ray strike the side of the cylinder before striking the bottom?
2. Recalling the definition of principal points, principal planes, and focal points, which of the following statements best describes the relationship between these quantities and the axis and surface of a compound lens system?
   (a) The focal points and principal points must lie on the axis and the principal planes must be perpendicular to the axis and lie inside the compound lens.
   (b) The focal points and the principal points must lie on the axis and the principal planes must intersect the axis at equal distances from the lens surfaces.
   (c) The focal points and the principal points must lie on the axis and the principal points must be at equal distances from the focal points.
   (d) The focal points and the principal points must lie on the axis and the principal planes must lie outside the compound lens.
3. For a converging lens of focal length 8 cm an object is placed 6 cm outside the focal point. The object is 4 cm high and the principal planes

are 2 cm apart.
  (a) Construct a principal ray diagram and locate the image.
  (b) From the diagram, determine the image height and the image distance.
4. For a diverging lens of focal length 8 cm an object is placed so that the object distance is 20 cm. The object is 4 cm high and the principal planes are 1 cm apart.
  (a) Construct a principal ray diagram and locate the image.
  (b) From the diagram, determine the image height and the image distance.
5. A ray of white light is incident on the boundary of glass and air, from the inside of the glass. The angle of incidence is precisely the critical angle for violet light. Describe what happens to the red part and the blue part of the incident light ray.

Test C-1
1. Suppose that you view a brick wall in a lab through a telescope. Two bricks are 0.4 cm high and they are 8 m away. The virtual image of these two bricks formed by the eyepiece is 1 cm high and 4 cm from your eye. What are the angles, in radians, subtended by the object for an unaided eye and by the virtual image for the aided eye? What is the angular magnification of this telescope?
2. A telescope has an eyepiece which has a focal length of 3 cm. The objective lens has a focal length of 30 cm. What is the angular magnification of the telescope?
3. In a 7 x 35 binoculars, what is the magnification? What are the diameters of the objective lens and the exit pupil?
4. A 7 x 35 monocular is used to look at the surface of the moon. How does the brightness of the image of the moon produced by this monocular compare with that of a telescope having an objective lens with a diameter of 75 mm and a focal length of 50 cm.
5. A large block of transparent material having an index of refraction of 1.55 has a ray of light incident to the boundary from the inside. What is the value of the critical angle?

Test C-2
1. Suppose that you view a doorway at the end of a hall through a telescope. The doorway is 2 m high and is 40 m away. The virtual image of the doorway formed by the eyepiece is 1.5 cm high and 5.5 cm from your eye. What are the angles, in radians, subtended by the object for an unaided eye and by the virtual image for the aided eye? What is the angular magnification of this telescope?
2. A telescope has an eyepiece which has a focal length of 2.5 cm. The objective lens has a focal length of 20 cm. What is the angular magnification of the telescope?
3. In an 8 x 50 binoculars, what is the magnification? What are the diameters of the objective lens and the exit pupil?
4. An 8 x 50 monocular is used to look at the surface of the moon. How does the brightness of the image of the moon produced by this monocular compare with that of a telescope having an objective lens with a diameter of 60 mm and a focal length of 40 cm? The eyepiece of the telescope has a focal length of 4 cm.
5. A large block of transparent material having an index of refraction of 1.62 has a ray of light incident to the boundary from the inside. What is the value of the critical angle?

SOLUTIONS TO POST-TESTS

Test A-1
1. (b)
2. The main parts are an objective lens and an eyepiece. The objective lens collects light from the object and forms a real image of the object.

The eyepiece magnifies the image that the objective lens produces.

3. The camera forms a real image since that image may be recorded on photographic film.
4. With one eye, look through the instrument at the even spaces. With the other eye look directly at those even spaces. You will see two images, one with each eye. Count how many spaces seen throught the unaided eye fit into one space seen with the aided eye. The ratio of these two spaces is the magnification.
5. The amount of light is proportional to $(D_1/D_2)^2$. Therefore, there is $(50/35)^2$ times more light in the 6 x 50 monocular exit pupil than in the 7 x 35 monocular exit pupil. This reduces to 25/12.3, or about 2 times as much light.

Test A-2

1. (c)
2. The main parts are an objective lens, the prism system, and the eyepiece. The objective lens collects light from the object and forms a real image of the object. The prism system shortens the light path and inverts the image. The eyepiece magnifies the image that the objective lens produces.
3. The camera forms a real image since that image may be recorded on photographic film.
4. With one eye, look through the instrument at the even spaces. With the other eye look directly at those even spaces. You will see two images, one with each eye. Count how many spaces seen through the unaided eye fit into one space seen with the aided eye. The ratio of these two spaces is the magnification.
5. The amount of light is proportional to $(D_1/D_2)^2$. Therefore, there is $(50/40)^2$ times more light in the 8 x 50 monocular exit pupil than in the 8 x 40 monocular exit pupil. This reduces to 25/16, or about 1.6 times as much light.

Test B-1

1. $\text{Sin } \theta_r = \frac{\sin 20°}{1.33} = \frac{0.342}{1.33}$

$= 0.259.$

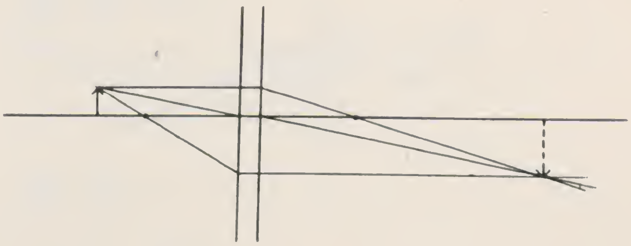
$\theta_r = 15°$

Then the radius of the glass divided by the distance below the brim that the light strikes the side is tan 15°.

Distance $= \frac{3.5 \text{ cm}}{0.268} = 13$ cm.

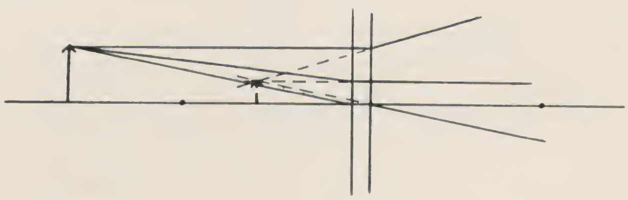
Since the glass is 15 cm high, the light will strike the glass at the wall 2 cm above the bottom.

2. (c)
3. (a)



(b) $H_i = 6$ cm; $x' = 20$ cm.

4. (a)



(b) $H_i = 1.2$ cm; $x' = 4$ cm.

5. Since the critical angle for red light is greater than the critical angle for the green and blue part of the spectrum, the entire incident ray will be totally internally reflected.

Test B-2

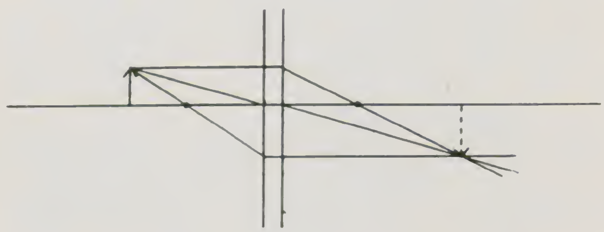
1. $\sin \theta_r = \frac{\sin 20°}{1.38} = \frac{0.342}{1.38} = 0.249$

   $\theta_r = 14°.$

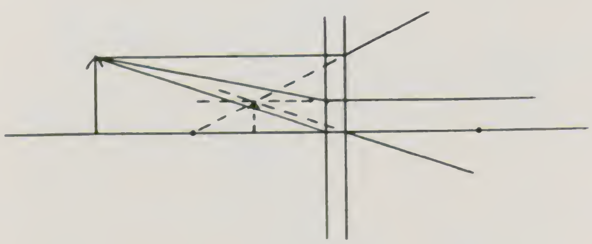
   Then the radius of the plastic cylinder divided by the distance down the side of the cylinder that the light strikes is tan 14°.

   Distance $= \frac{3\text{ cm}}{0.249} = 12$ cm

   Since the cylinder is 15 cm high, the light will strike the side 3 cm above the bottom.
2. (c)
3. (a)



   (b) $H_i = 5.3$ cm; $x' = 10.8$ cm.
4. (a)



   (b) $H_i = 1.6$ cm; $x' = 3.2$ cm.
5. Since the critical angle for red light is greater than the critical angle for violet light, the red, green, and blue part of the incident ray will be refracted at the boundary. The violet part of the ray will have an angle of refraction of 90°.

Test C-1

1. $\phi_u = \frac{0.4\text{ m}}{8\text{ m}} = 0.05$

   $\phi_a = \frac{1\text{ cm}}{4\text{ cm}} = 0.25$

   $M = \frac{\phi_a}{\phi_u} = \frac{0.25}{0.05} = 5$
2. $M = f_o/f_e = 30\text{ cm}/3\text{ cm} = 10$
3. $M = 7$; $D = 35$ mm.
   $d = D/M = 35\text{ mm}/7$
   $d = 5$ mm
4. $\frac{B_1}{B_2} = \left(\frac{D_1/M_1}{D_2/M_2}\right)^2$

   $D_1 = 35$ mm; $M_1 = 7$.
   $D_2 = 75$ mm; $M_2 = 50\text{ cm}/5\text{ cm} = 10$

   $\frac{B_1}{B_2} = \left(\frac{35\text{ mm}/7}{75\text{ mm}/10}\right)^2 = \left(\frac{10}{75} \times \frac{35}{7}\right)^2$

   $= \left(\frac{10}{15}\right)^2 = 0.44$

   The image seen through the monocular is 44% as bright as that seen through the telescope.
5. $\sin \theta_c = \frac{1}{n} = \frac{1}{1.55} = 0.645$

   $\theta_c = 40°.$

Test C-2

1. $\phi_u = \frac{2\text{ m}}{40\text{ m}} = 0.05$

   $\phi_a = \frac{1.5\text{ cm}}{5.5\text{ cm}} = 0.273$

$$\underline{M} = \frac{\phi_a}{\phi_u} = \frac{0.273}{0.05} = 5.5$$

2. $\underline{M} = \underline{f_o}/\underline{f_e} = 20 \text{ cm}/2.5 \text{ cm} = 8$

3. $\underline{M} = 8$; $\underline{D} = 50$ mm
$\underline{d} = \underline{D}/\underline{M} = 50 \text{ mm}/8$
$\underline{d} = 6.25$ mm

4. $$\frac{\underline{B_1}}{\underline{B_2}} = \left(\frac{\underline{D_1}/\underline{M_1}}{\underline{D_2}/\underline{M_2}}\right)^2$$

$\underline{D_1} = 50$ mm; $\underline{M_1} = 8$
$\underline{D_2} = 60$ mm; $\underline{M_2} = 40 \text{ cm}/4 \text{ cm} = 10$

$$\frac{\underline{D_1}}{\underline{B_2}} = \left(\frac{50 \text{ mm}/8}{60 \text{ mm}/10}\right)^2 = \left(\frac{10}{60} \times \frac{50}{8}\right)^2$$

$$= \left(\frac{50}{48}\right)^2 = 1.1.$$

The image seen through the monocular is 1.1 times as bright as that seen through the telescope.

5. $$\sin \theta_c = \frac{1}{\underline{n}} = \frac{1}{1.62} = 0.618$$

$$\theta_c = 38°$$

IX LIST OF APPARATUS

Experiment A-1
Monocular
(or binoculars)
Optical bench
Adjustable diaphragm or several fixed diaphragms
Ground glass screen
Lens holder for the optical bench (3)
Ruler (in cm and inches)

Experiment A-2
Optical bench
Lens holder for optical bench (3)
Converging lenses (2) (different focal lengths from 5-50 cm)
Ground glass screen
Prism system (to invert the image)

Experiment B-1
Hartl optical disc
(or equivalent)
Collimated light source
Semicircular glass plate

Experiment B-2
Optical bench
Lens holder for optical bench (3)
Diverging lens
Light source (for optical bench)
White screen with holder
Lab telescope
Angle measuring device (surveyor's transit, spectrometer table, or any device with 0.1° precision)
Cathetometer

Experiment C-1
Optical bench
Thin converging lens
(6)(different focal lengths)
Lens holder for optical bench (2)

Experiment C-2
Monocular
Optical bench
Lens holder for optical bench (2)
Ground glass screen
Adjustable diaphragm
Vernier caliper (or cathetometer or traveling microscope)

OPTIONAL DEMONSTRATION AIDS

16 mm Sound Films
1. "Lenses." 15 min., B & W. United World Films; available through University of Illinois Film Library.
2. "The Refraction of Light." Color; Cenco Educational Films.

8 mm Film Loops
1. "Models of Reflection and Refraction." Gateway Educational Film Ltd.
2. "Image Formation by Convex Lenses." United World Films, Inc.
3. "Concave Lenses." United World Films, Inc.

Transparencies

1. "Real Image." No. M-6727, Frey Scientific Company.
2. "Index of Refraction." No. F-6764, Frey.
3. "Image Formed by a Convex Lens." No. F-6765, Frey.
4. "Image Formed by a Concave Lens." No. F-6766, Frey.
5. "Geometrical Optics." Set of 7, No. E-101, Lansford Publishing Co.

CONTENTS

I INTRODUCTION

The subject matter of the Camera module is geometrical optics, which is typically treated in the second semester. However, the module may be used at any point in a course, since it has no physics prerequisites.

The module emphasizes: real and virtual image formation by various apertures and lenses; refraction of light; focal points, focal planes, focal lengths, and lateral magnification for converging lenses; and chromatic and spherical aberrations. The technique of image determination from a principal ray diagram is introduced.

The principles treated include: the empirical relationship between image position, object position, and focal length; the relationship between lateral magnification, object position, and focal length; the relationship of brightness of an image to aperture diameter and focal length (for images formed with a lens).

II SPECIAL PREREQUISITES

There are no special prerequisites for this module except that for the Physics of Technology series as a whole: high school algebra.

III TABLE OF CONTENTS OF THE MODULE

Experiment C-1. Compound Lenses
Thin and Compound Lenses
An Operational Definition of Focal Length
Amount of Light Entering a Lens
Brightness of a Camera Image
Camera Exposure Times
Camera f Numbers
Film Speed
Experiment C-2. Using a Camera
Work Sheets

IV GOALS

The goals of the Camera module have been included at the beginning of each section of the module.

V DISCUSSION OF ACTIVITIES

The module is divided into three parts, each representing one week's study

SECTION A

The first section is largely qualitative. The student is introduced to the pinhole camera, the camera obscura, and the lens camera in the lab, and he makes several observations which raise questions for which answers are not yet provided. The first section concludes with a discussion of image formation by lenses and the principles which explain some of the students' observations, and a summary of the qualitative principles and concepts they have learned.

Experiment A-1 should be completed early in the week. Experiment A-2 may be completed later in the week. If time doesn't permit both experiments to be completed by the student, Experiment A-2 may be done as a demonstration in class.

During this first week, class time might be devoted to the following activities:

First Class Period

1. Show and explain different kinds of lens cameras. Show pinhole camera and camera obscura.
2. Explain light sources, light rays, and image production through a small hole on a screen.
3. Discuss Questions 1, 2, 3, and 4 and Experiment A-1 in terms of what is to be done and how data are analyzed.

Experiment A-1. The Pinhole Camera

The purposes of this experiment are: first, to familiarize the student with the camera and photographic process that is to be used throughout the module; to have the student learn how the correct exposure time depends on the pinhole size; and to compare the sharpness and depth of field in photographs from the pinhole camera and the lens camera. The second part of the experiment has the student: observe the inverted image in a camera obscura (the film and back of the camera are replaced by a viewing screen); observe the change in image size and brightness as the distance from pinhole to screen is changed; observe the effect of pinhole size on the sharpness and brightness of the image; observe the infinite depth of field of the pinhole camera; and observe the improvement in brightness but loss of depth of field when a lens is placed in front of the pinhole.

This experiment raises questions about the physics of the camera, most of which are answered through observations or descriptions in the module. Most of the quantitative and analytical material of the module is based on the qualitative observations students make in this experiment.

Second Class Period

1. Discuss some of the steps and questions of Experiment A-1. Ask about results students are getting and how these results should be interpreted.
2. Discuss the history of the camera obscura, and the effect of adding a lens to the camera aperture.

Experiment A-2. Observations of Lenses; Refraction

The purposes of this experiment are: for the student to observe, qualitatively, the image formed by a single converging lens; to observe chromatic and spherical aberration effects in a thin converging lens and the lack of chromatic aberration in an achromatic lens; and to observe, qualitatively, the refraction of light rays at glass-air interfaces as the angle between the light ray and the normal to the surface is varied.

Third Class Period

1. Discuss the results of Experiment A-2, or do it as a class demonstration.
2. Summarize properties of lenses: refraction, focal length, and aberration.
3. Discuss those Section A goals and sample items for which the students need further explanation.
4. Administer Section A post-test (5 items, 25 minutes).

SECTION B

The second section of the module defines focal length for a converging lens and has the student arrive empirically (in the lab) at the relationship between image position, object position, and focal length and the relationship between lateral magnification and focal length. The empirical equations are discussed quantitatively with appropriate problems and exercises. The method of determining image formation in a converging lens by means of principal ray diagrams is introduced. The section concludes with applications of lens principles to the camera and a summary of principles and concepts the student has learned.

The teacher may want to use the following activities in this second week of study:

First Class Period

1. Discuss Experiment B-1 in terms of what is to be done and how data are analyzed.
2. Show film, "Lenses" (15 minutes).

Experiment B-1. Location and Sizes of Images

Experiment B-1 should be completed very early in the week.

The purposes of this experiment are: to define and measure focal length for a converging lens; to define and measure object and image distances for a converging lens; to graphically determine the inverse proportionality between image distance for a converging lens; to have the student find, empirically, the lens equation: $xx' = f^2$; to define and measure object height and image height for a converging lens; to graphically determine the inverse proportionality between image height and object distance; and to have the student find, empirically, the lateral magnification equation, $H_i/H_o = f/x$.

Second Class Period

1. The results of Experiment B-1 should be discussed.
2. Discuss Problems 1, 2, 3, and 4.
3. Explain and practice principal ray diagrams.

Third Class Period

1. Discuss image size and focussing with a camera.
2. Discuss those Section B goals and sample items for which students still need explanation.
3. Administer Section B post-test (5 items, 25 minutes).

SECTION C

Section C derives the lens equations from the principal ray diagram of a converging lens, and extends the lens principles to compound lenses (such as might be found in a camera). Some parameters in photography (f number, exposure time, and film speed) are discussed quantitatively in terms of the principles, definitions, and concepts of lenses with appropriate

problems and exercises. The section concludes with a laboratory verification of the relationship between f numbers, film speed, exposure time, and the settings for a camera.

The student should do Experiment C-1 early in the week and Experiment C-2 later in the week. If both experiments cannot be done in the lab, Experiment C-2 may be done as a demonstration.

The following activities might be used:

First Class Period

1. Discuss the concept of similar triangles and ratios. Ask a sequence of questions to get members of the class to deduce the lateral magnification and lens equations: $\underline{H_i}/\underline{H_o} = \underline{f}/\underline{x}$, and $\underline{xx'} = \underline{f}^2$.
2. Discuss objects inside the focal point of a converging lens (the magnifying glass).
3. Discuss Experiment C-1 in terms of what is to be done and how data are analyzed.

Experiment C-1. Compound Lenses

The purposes of this experiment are: to have the student discover that the focal points are not symmetrical about the center for a lens system or compound lens; that the lens equations, $\underline{xx'} = \underline{f}^2$ and $\underline{H_i}/\underline{H_o} = \underline{f}/\underline{x}$, apply to compound lenses as well as to thin lenses; and that the focal length of a compound lens can be determined from the focal length of a thin lens that produces the same size image as the compound lens.

Second Class Period

1. Discuss the results of Experiment C-1.
2. Discuss focal length and Problems 12, 13, and 14.
3. Discuss amount of light entering a lens and the brightness of the image.
4. Discuss Experiment C-2 in terms of what is to be done.

Experiment C-2. Using a Camera

The purpose of this experiment is to use the relationship between f number, film speed, and exposure time, derived in the module, to predict the settings for a camera to produce a properly exposed picture. This experiment should be done under the same conditions and with the same scene and lighting as Experiment A-1. Due to minor differences between Polaroid type 108 color film packets, proper color exposure times may not be the same as the times calculated from the black and white exposure times.

Third Class Period

1. Discuss adjustment of camera parameters: film speed, exposure time, and f numbers using the cameras demonstrated in the first class period of Week 1.
2. Discuss the results of Experiment C-2.
3. Discuss those Section C goals and test items for which students still need explanation.
4. Administer the post-test for Section C (5 items, 25 minutes).

VI SAMPLE DATA

Experiment A-1

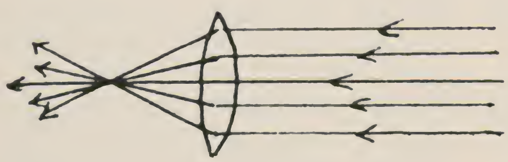
1. Yes. Proper exposure time for a 0.25-mm-diameter pinhole should be approximately 1 minute.
2. Approximately 15 seconds.
3. Approximately 5 seconds.
4. 0.25-mm pinhole gave a sharper picture.
5. Yes.
6. Exposure time is proportional to $1/\text{diameter}^2$.
7. About 1/2 second.
8. Some objects appear sharper in this picture than in the pinhole pictures.
9. No.
10. The image is upside down and reversed right and left.
11. (Most answers to this questions are incorrect or at best incomplete.)
12. Image becomes larger as the pinhole is moved away from the screen and

smaller as the pinhole is moved closer to the screen.

13. The image becomes brighter as the pinhole is moved closer to the screen and dimmer as the pinhole is moved away from the screen.
14. The image becomes sharper as the pinhole is moved closer to the screen and less sharp as the pinhole is moved away from the screen.
15. As the size of the opening in the diaphragm is increased, the image size remains the same, the image brightness increases, but the image sharpness decreases.
16. Image sharpness does not appear to change.
17. About the same.
18. No.
19. The image should be sharp, depending upon the pinhole to screen distance.
20. About the same.
21. Yes.
22. Yes. There is a minimum distance that will produce a sharp image.

Experiment A-2

1. Clear inverted image through both lenses. (usually smaller than the object.)
2. Upside down, backwards image.
3. Red.
4. Less red (greenish or blueish to some).
5. No.
6. 31.6 cm.
7. 30.4 cm.
8. No.
9. Larger.
10. The light ray is always normal to the glass-air surface.
11. It gets larger.
12. Increases.
13.



Experiment B-1

1. Yes
2.
3. Yes. Lens A $\underline{f}$ = 20.1 cm
   Lens B $\underline{f}$ = 9.8 cm
   Lens C $\underline{f}$ = 5.1 cm

4. Lens A

Trial	x	x'
1	32.0 cm	12.0 cm
2	27.0 cm	14.6 cm
3	22.6 cm	20.2 cm
4	17.0 cm	22.3 cm
5	12.0 cm	26.2 cm

Lens B

Trial	x	x'
1	42.7 cm	2.2 cm
2	37.7 cm	2.7 cm
3	32.7 cm	2.8 cm
4	27.7 cm	3.5 cm
5	22.7 cm	3.8 cm

Lens C

Trial	x	x'
1	47.4 cm	0.3 cm
2	42.4 cm	0.4 cm
3	37.4 cm	0.5 cm
4	32.4 cm	0.6 cm
5	27.4 cm	0.7 cm

5. $\underline{x}'$ decreases as $\underline{x}$ increases.
6. No.
7. Yes.
8. Lens A slope = 370 cm^2.
9. Lens B slope = 100 cm^2.
   Lens C slope = 20 cm^2.
10. Slope $\approx \underline{f}^2$.
11. $\underline{xx}' = \underline{f}^2$.
12. 3.5 cm.
13. 2.7 cm.
14. Image height increases as the object is moved closer to the lens.
15. (For $\underline{f}$ = 20.0 cm)

Trial	H_o	H_i	x	x'
1	3.5 cm	13.1 cm	5 cm	74.0 cm
2	3.5 cm	6.6 cm	10 cm	38.0 cm
3	3.5 cm	4.3 cm	15 cm	24.0 cm
4	3.5 cm	3.3 cm	20 cm	19.0 cm
5	3.5 cm	2.7 cm	25 cm	14.5 cm

16. As the object distance increases, the image size decreases.
17. No.
18. 65.3 cm^2.
19. $\underline{H_o f} = 70\ cm^2 \approx 65.3\ cm^2 = \underline{H_i x}$

Experiment C-1

1. Position of one focal point = 60 cm. Distance to the center of the system = 10.0 cm.
2. Position of the other focal point = 0.0 cm. Distance to the center of the lens = 50.0 cm.
3. $\underline{x}$ = 23.5 cm, $\underline{H_o}$ = 3.4 cm.
4. $\underline{x}'$ = 19 cm, $\underline{H_i}$ = 3.0 cm.
5. $\underline{f}$ = 21 cm.
6. $\underline{H_i}/\underline{H_o}$ = 0.87.
   The ratio $\underline{H_i}/\underline{H_o}$ is nearly the same as $\underline{f}/\underline{x}$, which is 0.85.
7. $\underline{f}$ = 20 cm.

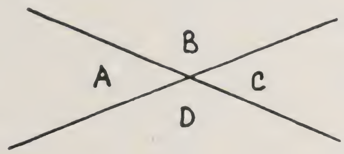
Experiment C-2

1. Black and white exposure time: about 5 minutes.
2. Color exposure time: about 200 seconds.
3. About the same.
4. Pinhole f number is about f/22.
5. Lens f number is about f/4.
6. Calculated exposure time is about 3 seconds.
7. The color picture is about the same quality as the black and white picture except that not all objects are in focus in the color picture.

VII SOLUTION TO PROBLEMS

The problems and questions are an important part of the module and should be discussed in class, if possible.

1. 20 cm.
2. 2.
3. $\underline{x}'$ = 20 cm; $\underline{H_i}$ = 10 cm.
4. 15 cm from the lens.
5. 60 cm from the lens.
6. 7.5 cm from the lens;
   $\underline{H_i}$ = 1.5 cm.
7. 1.05 mm; 31.05 mm.
8. 1650 mm.
9. 1.20 cm.
10. Two intersecting straight lines form two pairs of vertical angles: A and C, B and D.



From the definition of supplementary angles: A + B = 180°, and B + C = 180°.
Subtracting these:

$$\begin{array}{r} A + B = 180^\circ \\ \underline{-B - C = -180^\circ} \\ A - C = 0^\circ \\ A = C \end{array}$$

11. Similar to Figure 23.
12. 42.5 cm.
13. 1.6 cm.
14. 200 mm.
15. 16 times as much.
16. 1/9 the brightness of the 50-mm lens.
17. The brightness will increase by a factor of 4.
18. f/3.
19. 1200 mm.
20. f/4.

VIII POST-TESTS

Test A-1

1. Suppose that you are viewing the image of a large clock on the wall through a camera obscura with a small aperture. The time of day is 3:00 p.m.
   (a) Sketch the image as you would view it.
   (b) Sketch the image you would view if the screen were moved farther away from a large aperture.
   (c) Sketch the image you would view with a small aperture if the camera obscura were turned upside down, but still faced the clock.

2. Suppose that the camera obscura of Question 1 is modified by placing a converging lens in front of the fully opened aperture. Which of the following statements best describes the change in the image over that seen when no lens is in front of the fully opened aperture?
   (a) The brightness of the image increases, the sharpness of parts of the image increases, the other parts of the image remain blurred, and the size of the image increases.
   (b) The brightness of the image remains the same, the sharpness of parts of the image increases, the other parts of the image remain blurred, and the size of the image increases.
   (c) The brightness of the image remains the same, the sharpness of parts of the image increases, the other parts of the image remain blurred, and the size of the image remains the same.
3. A single thin converging lens is used to produce an image of the filament of a clear incandescent lamp on a movable screen. If a blue filter (a material which allows only blue light to pass through it) is placed between the lamp and the lens, which of the following statements best describes the effects on the image that is produced on the screen?
   (a) The screen must be moved closer to the lens in order to obtain the sharpest image of the filament.
   (b) The screen must be moved farther from the lens in order to obtain the sharpest image of the filament.
   (c) There is no effect on the image.
4. Recalling the definitions of the two focal points and the object point and image point for a converging lens, which of the following statements best describe the position of these points relative to the axis of a single thin converging lens when the object is farther from the lens than the focal point?
   (a) The focal points and the object and image points must lie on the axis.
   (b) The focal points must lie on the axis and the image point and and object point may lie on the axis.
   (c) The focal points may lie on the axis and the image point and object point may not lie on the axis.
   (d) The focal points and the image point and object point must lie in a straight line.
5. In order for a light ray to undergo refraction at the surface between two different materials, which of the following statements best describes the situation when refraction takes place?
   (a) The incident ray must be at some angle greater than zero degrees with respect to the normal to the surface, and the refracted ray must make an angle with the normal to the surface which is greater than the angle that the incident ray makes with the normal.
   (b) The incident ray may be at some angle greater than zero degrees with respect to the normal to the surface, and the refracted ray may make an angle with the normal to the surface which is greater than the angle that the incident ray makes with the normal.
   (c) The incident ray must be at some angle greater than zero degrees with respect to the normal to the surface, and the refracted ray may make an angle with the normal to the surface which is greater than the angle that the incident ray makes with the normal.
   (d) The incident ray may be at some angle greater than zero degrees with respect to the normal to the surface, and the refracted ray

must make an angle with the normal to the surface which is greater than the angle that the incident ray makes with the normal.

Test A-2

1. Suppose that you are viewing the image of an "EXIT" sign in a building through a camera obscura with a small aperture.
   (a) Sketch the image as you would view it.
   (b) Sketch the image you would view if the screen were moved farther away from a large aperture.
   (c) Sketch the image you would view with a small aperture if the camera obscura were turned upside down, but still facing the "EXIT" sign.
2. Suppose that the camera obscura of Question 1 is modified by placing a converging lens in front of the small aperture. Which of the following statements best describes the change in the image over that seen when no lens is in front of the small aperture?
   (a) The brightness of the image increases, the sharpness of the image increases, and the size of the image increases.
   (b) The brightness of the image remains the same, the sharpness of the image increases, and the size of the image increases.
   (c) There is almost no effect on the image.
3. A single thin converging lens is used to produce an image of the filament of a clear incandescent lamp on a movable screen. If a blue filter (a material which allows only blue light to pass through it) is placed between the lamp and the lens, which of the following statements best describes the effects on the image that is produced on the screen?
   (a) The screen must be moved closer to obtain the sharpest image of the filament.
   (b) The screen must be moved farther from the lens in order to obtain the sharpest image of the filament.
   (c) There is no effect on the image.
4. Make a sketch of the side view of a thin converging lens with an axis through the lens, an object farther from the lens than the focal point, and an image. On the sketch, identify two focal points, an object point, and a corresponding image point.
5. Make a sketch of a light ray which strikes a glass surface from air and makes some angle with respect to the normal to the surface. Sketch the surface, the normal to the surface, and the incident and refracted rays.

Test B-1

(A centimeter ruler should be supplied with this test and the student should be instructed to use a full 8-1/2 x 11 sheet of paper for principal ray diagrams. The back of a page on this test would do nicely.)

1. You should recall from the module, as well as from experience, that as you move a camera closer to an object, the image that you see through the camera gets larger. As you back away from your subject, the image that you see gets smaller. Express the relationship between object distance and image height in the form of a proportion.
2. For a converging lens of focal length 10 cm, an object is placed 25 cm from the lens. The object is 3 cm high.
   (a) Construct a principal ray diagram and locate the image.
   (b) From the diagram, determine the image height and the distance from the image to the lens.
3. An object having a height of 5 cm is located 20 cm from a lens having a focal length of 15 cm. Using equations, find the image height.
4. A converging lens has an object located

at a distance $\underline{x_1}$ from the focal point (in a direction away from the lens). For this position of the object, the image is located 9 cm beyond the focal point on the other side of the lens. Suppose that we replace this lens with another lens having one-third the focal length of the first lens. Then we adjust the object position so that it is again a distance $\underline{x_1}$ from the focal point.
(a) Which way must we move the object to make this adjustment?
(b) Calculate the value of the new image distance.

5. Suppose that you are designing a camera using a converging lens with a focal length of 135 mm. The design specifications require that the camera focus on objects from as close as 4.0 feet (122 cm) from the film plane out to infinity.
   (a) What width (minimum distance from lens to film plane) will you select for the camera case?
   (b) How far must it be possible to move the lens from when it is focused on objects at infinity to when it is focused on objects at 4.0 feet?
   (c) How high will the image be on the film for a tree 30 feet high (910 cm) which is 600 feet (18,200 cm) away?

Test B-2

(A centimeter ruler should be supplied with this test and the student should be instructed to use a full 8-1/2 x 11 sheet of paper for principal ray diagrams. The back of a page on this test would do nicely.)

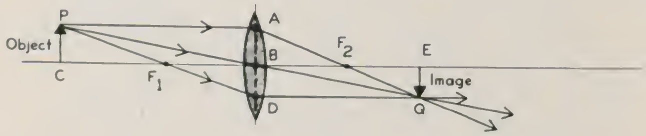
1. A "telephoto" lens on a camera is used to make distant objects appear near; that is, to make the image height larger for some given distant object. The telephoto lens has a larger focal length than an ordinary lens has. Express the relationship between focal length and image height in the form of a proportion.
2. For a converging lens of focal length 15 cm, an object is placed 25 cm from the lens. The object is 4 cm high.
   (a) Construct a principal ray diagram and locate the image.
   (b) From the diagram, determine the image height and the distance from the image to the lens.
3. An object having a height of 4 cm is located 25 cm from a lens having a focal length of 15 cm. Using equations, find the image height.
4. A converging lens has an object located at a distance $\underline{x_1}$ from the focal point (in a direction away from the lens). For this position of the object the image is located 15 cm beyond the focal point on the other side of the lens. Suppose that we replace this lens with another lens having twice the focal length of the first lens. Then we adjust the object position so that it is again a distance $\underline{x_1}$ from the focal point.
   (a) Which way must we move the object to make this adjustment?
   (b) Calculate the value of the new image distance.
5. Suppose that you are designing a camera using a converging lens with a focal length of 200 mm. The design specifications require that the camera focus on objects from as close as 6.0 feet (182 cm) from the film plane out to infinity.
   (a) What width (minimum distance from lens to film plane) will you select for the camera case?
   (b) How far must it be possible to move the lens from when it is focused on objects at 6.0 feet?
   (c) How high will the image be on the film for a tree 30 feet high (910 cm) which is 600 feet (18,200 cm) away?

Test C-1

(A centimeter ruler should be supplied with this test and the student should be instructed to use a full 8-1/2 x 11 sheet of paper for principal ray diagrams. The

back of a page on this test would do nicely.)

1. Referring to the principal ray diagram shown below, identify the similar triangles which would be used to derive the equation $\underline{H_i}/\underline{H_o} = \underline{x}'/\underline{f}$.



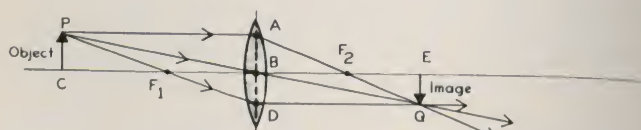
(Designate each triangle by the symbol Δ in front of three letters which are at the vertices of the triangle, as in ΔPCF_1.)

2. A thin converging lens of focal length 10 cm has an object of height 3 cm placed on the axis 5 cm from the lens.
   (a) Construct a principal ray diagram.
   (b) From your diagram, determine the distance from the image to the lens.
   (c) From your diagram, determine the height of the image.
   (d) What is the name we give to this kind of an image?
3. The disc (diameter) of the planet Jupiter subtends an angle of 1/600 radian, as observed at the location of a certain lens. If the image of Jupiter formed by this lens has a diameter of 2 mm (0.2 cm), what is the focal length of the lens?
4. Some typical f numbers on a camera lens are: 1.4; 2; 2.8; 4; 5.6; 8; 11; 16; 22. If the lens has a focal length of 85 mm:
   (a) What is the diameter of the lens aperture for an f number of 2.8?
   (b) How much brighter is the image for an f number of 2.8 than for an f number of 5.6?
5. Suppose that, to get a correct exposure using ASA 25 film, you have to set your camera at 1/60 second and f/5.6. If someone else has a camera which is loaded with ASA 160 film, and which is set at f/11, what shutter speed is needed for a correct exposure with this camera?

Test C-2

(A centimeter ruler should be supplied with this test and the student should be instructed to use a full 8-1/2 x 11 sheet of paper for principal ray diagrams. The back of a page on this test would do nicely.)

1. Referring to the principal ray diagram shown below, identify the similar triangles which would be used to derive the equation $\underline{H_i}/\underline{H_o} = (\underline{x}' + \underline{f})/(\underline{x} + \underline{f})$.



2. A thin convering lens of focal length 20 cm has an object of height 5 cm placed on the axis 5 cm from the lens.
   (a) Construct a principal ray diagram.
   (b) From your diagram, determine the distance from the image to the lens.
   (c) From your diagram, determine the height of the image.
   (d) What is the name we give to this kind of an image?
3. A building subtends an angle of 1/10 radian, as observed at the location of a certain lens. If the image of the building formed by this lens is 5 mm high, what is the focal length of the lens.
4. Some typical f numbers on a camera lens are: 1.4; 2; 2.8; 4; 5.6; 8; 11; 16; 22. If the lens has a focal length of 135 mm:

(a) What is the diameter of the lens aperture for an f number of 16?

(b) How much brighter is the image for an f number of 4 than for an f number of 16?

5. Suppose that, to get a correct exposure using ASA 32 film, you have to set your camera at 1/60 second and f/5.6. If someone else has a camera which is loaded with ASA 64 film, and which is set at f/8,what shutter speed is needed for a correct exposure with this camera?

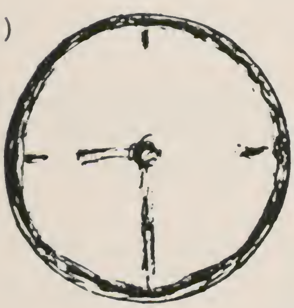
ANSWERS TO POST-TESTS

Test A-1

1.

a)

b)



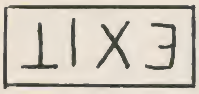
c)

2. (c)
3. (a)
4. (b)
5. (c)

Test A-2

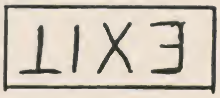
1.

a)

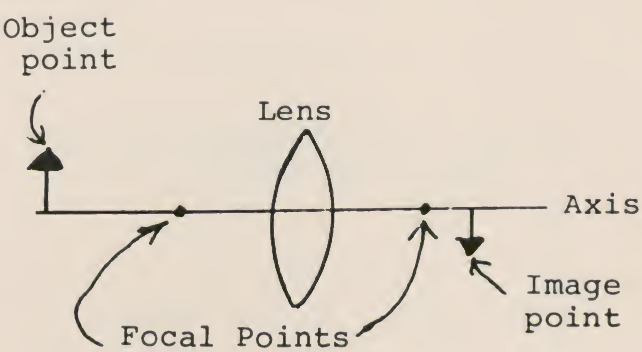


b)

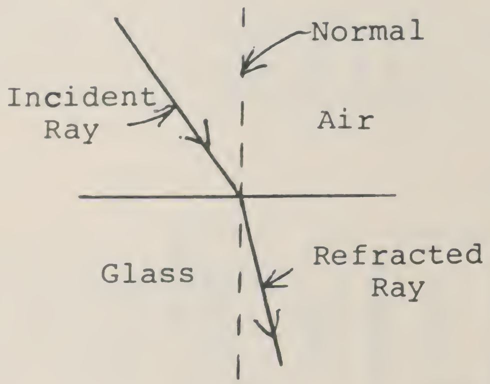
c)



2. (c)
3. (a)
4.

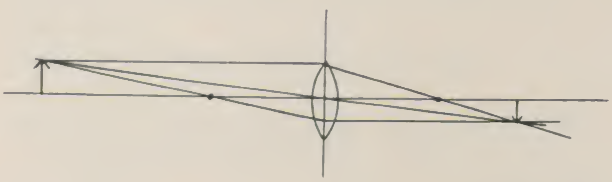


5.



Test B-1

1. $\underline{H_i} \propto 1/\underline{x}$. Image height is inversely proportional to object position.
2. (a)



(b) $\underline{H_i} \simeq$ 2 cm; distance from the image to the lens $\simeq$ 17 cm.

3. $\underline{H_i} = \underline{H_o}\,\underline{f}/\underline{x}$

$\underline{H_i}$ = 5 cm x 15 cm/5 cm

$\underline{H_i}$ = 15 cm

4. (a) + = away from the lens.
   - = toward the lens.

$\underline{L_2} - \underline{L_1} = \underline{x_2} + \underline{f_2} - \underline{x_1} - \underline{f_1}$

$\underline{L_2} - \underline{L_1} = \underline{f_2} - \underline{f_1}$

$\underline{L_2} - \underline{L_1} = \underline{f_1}/3 - \underline{f_1}$

$\underline{L_2} - \underline{L_1} = -(2/3)\underline{f_1}$

Object must be moved toward the lens.

(b) $\underline{x}'_1 \propto \underline{f_1}^2, \quad \underline{x}'_2 \propto \underline{f_2}^2$

$$\underline{x}'_2 = \frac{\underline{f_2}^2}{\underline{f_2}^2}\,\underline{x}'_1 = \frac{(\underline{f_1}/3)^2}{\underline{f_1}^2} \cdot 9 \text{ cm}$$

$$\underline{x}'_2 = \frac{9 \text{ cm}}{9} = 1 \text{ cm}$$

5. (a) 135 mm

(b) $\underline{x}' \simeq \dfrac{\underline{f}^2}{\underline{L}} \simeq \dfrac{(135 \text{ mm})^2}{1220 \text{ mm}} \simeq \dfrac{18{,}200 \text{ mm}}{1200 \text{ mm}}$

$\underline{x}' \simeq 15$ mm

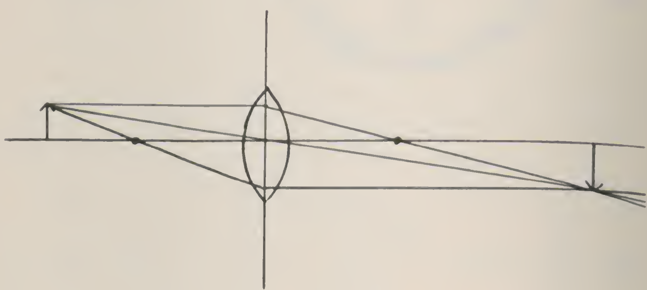
(c) $\underline{H_i} = \underline{H_o}\,\underline{f}/\underline{x}$

$= 9100 \text{ mm x } \dfrac{135 \text{ mm}}{182{,}000 \text{ mm}}$

$\underline{H_i}$ = 7.7 mm

Test B-2

1. $\underline{H_i} \propto \underline{f}$. Image height is directly proportional to focal length.
2. (a)



(b) $\underline{H_i} \simeq$ 5.5 cm; distance from the image to the lens $\simeq$ 36 cm.

3. $\underline{H_i} = \underline{H_o}\,\underline{f}/\underline{x}$ = 4 cm x 15 cm/10 cm

$\underline{H_i}$ = 6 cm

4. (a) + = away from the lens.

- = toward the lens.

$\underline{L}_2 - \underline{L}_1 = \underline{x}_2 + \underline{f}_2 - \underline{x}_1 - \underline{f}_1$

$\underline{L}_2 - \underline{L}_1 = \underline{f}_2 - \underline{f}_1$

$\underline{L}_2 - \underline{L}_1 = 2\underline{f}_1 - \underline{f}_1$

$\underline{L}_2 - \underline{L}_1 = \underline{f}_1$

Object must be moved away from the lens.

(b) $\underline{x}_1' \propto \underline{f}_1{}^2,\ \underline{x}_2' \propto \underline{f}_2{}^2,$

$$\underline{x}_2' = \frac{\underline{f}_2{}^2}{\underline{f}_1{}^2}\,\underline{x}_1' = \frac{2\underline{f}_1{}^2}{\underline{f}_1{}^2} \times 15 \text{ cm}$$

$\underline{x}_2' = 4 \times 15 \text{ cm} = 60 \text{ cm}$

5. (a) 200 mm

(b) $$\underline{x}' \simeq \frac{\underline{f}^2}{\underline{L}} \simeq \frac{(200 \text{ mm})^2}{1820 \text{ mm}}$$

$$= \frac{40{,}000 \text{ mm}^2}{1820 \text{ mm}}$$

$\underline{x}' \cong 22$ mm

(c) $\underline{H}_i = \underline{H}_o\underline{f}/\underline{x}$

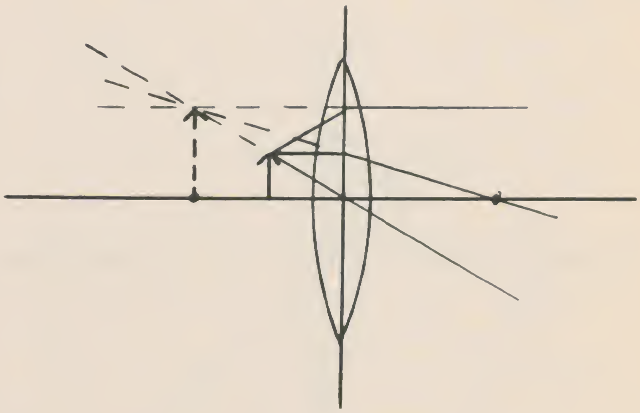
$$= 9100 \text{ mm} \times \frac{200 \text{ mm}}{182{,}000 \text{ mm}}$$

$\underline{H}_i = 10$ mm

Test C-1

1. ΔABF_2 is similar to ΔQEF_2.

2. (a)



(b) Distance $\simeq$ 10 cm.

(c) $\underline{H}_i \simeq 6$ cm.

(d) Virtual image.

3. $$\underline{f} = \underline{H}_i/\alpha = \frac{2 \text{ mm}}{1/600} = 1200 \text{ mm}$$

$\underline{f} = 120$ cm.

4. (a) f number = $\underline{f}/\underline{D}$,

$\underline{D} = \underline{f}$/f number

= 85 mm/2.8

$\underline{D} \simeq 30$ mm = 3 cm

(b) $$\underline{B} \propto \frac{1}{(\text{f number})^2}$$

$$\underline{B}_2 = \left(\frac{\text{f number}_1}{\text{f number}_2}\right)^2 \underline{B}_1$$

$$= \left(\frac{5.6}{2.8}\right)^2 \underline{B}_1 = 4\underline{B}_1$$

Brightness is 4 times as much.

5. $$\frac{\underline{Z}_2}{\underline{Z}_1} = \left(\frac{\text{f number}^2}{\text{f number}^1}\right)^2 \frac{\underline{Z}_1}{\underline{Z}_2}\ \underline{t}_1$$

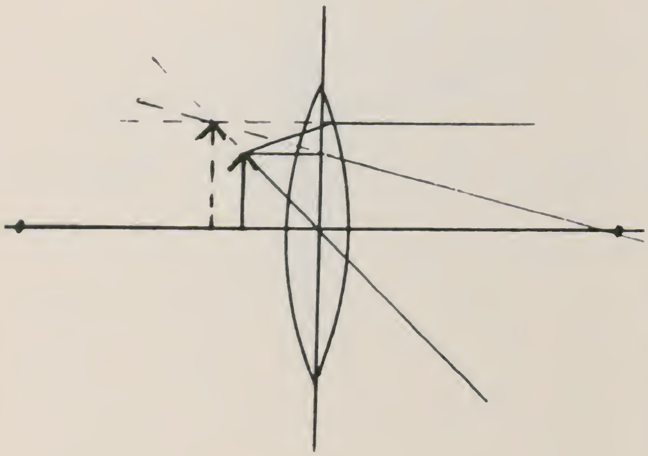
$$\underline{t}_2 = \left(\frac{\text{f number}_2}{\text{f number}_1}\right)^2 \frac{\underline{Z}_1}{\underline{Z}_2}\ \underline{t}_1$$

$$\underline{t}_2 = \left(\frac{11}{5.6}\right)^2 \times \frac{25}{160} \times 1/60 \text{ second}$$

$\underline{t}_2 \simeq 1/100$ second

Test C-2

1. ΔGEB is similar to ΔPCB.
2. (a)



(b) Distance $\simeq$ 7 cm

(c) $H_i \simeq 7$ cm

(d) Virtual image.

3. $f = H_i/\alpha = \dfrac{5\text{ mm}}{1/10} = 50\text{ mm}$

4. (a) f number = f/D

$D = f/\text{f number} = 135\text{ mm}/16$

$D \cong 8.5\text{ mm}.$

(b) $B_2 = \left(\dfrac{\text{f number}_1}{\text{f number}_2}\right)^2 B_1 = \left(\dfrac{16}{4}\right)^2 B_1 = 16B_1$

Brightness is 16 times as much.

5. $t_2 = \left(\dfrac{\text{f number}_2}{\text{f number}_1}\right)^2 \quad B_1 = \dfrac{Z_1}{Z_2}\, t_1$

$t_2 = \left(\dfrac{8}{5.6}\right)^2 \times \dfrac{32}{64} \times 1/60\text{ second}$

$= 2 \times \dfrac{32}{64} \times 1/60\text{ second}$

$t_2 = 1/60\text{ second}$

IX LIST OF APPARATUS

Experiment A-1

Polaroid Model 420 camera (or equivalent)

Polaroid type 107 black & white film pack

Mounted pinholes (0.25 mm, 0.5 mm, and 1.0 mm diameter)

Mounted lens with 5-mm-diameter aperture (focal length 10 cm or less)

Adjustable diaphragm

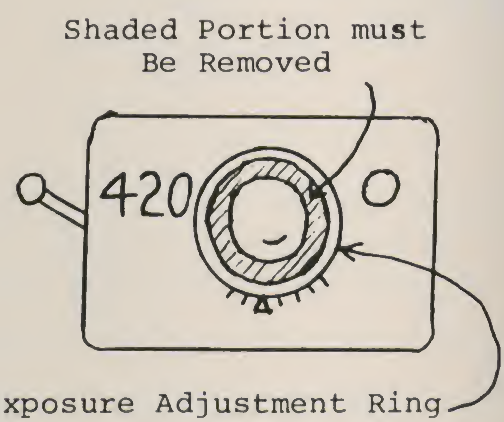
Mounted translucent screen for back of Polaroid camera

Note

The camera that is to be used in the experiments should be able to accept Polaroid type film, so that lab results may be obtained in a reasonable length of time. The authors recommend the Polaroid Model 420. This camera not only is the easiest model to modify as a pinhole camera obscura but also makes a good laboratory camera for multiflash photography in the study of motion, such as on an air track or air table. The modification described below is for the Polaroid Model 420. This modification does not permanently damage the camera. A similar modification may be made on other Polaroid cameras.

Polaroid Model 420 Modification

In order for the lenses to be removed so that pinholes may be attached, it is necessary to cut away the inner cone of the plastic exposure adjustment ring surrounding the front lens, as in the figure.



The exposure adjustment ring may be removed for cutting by prying off the front plate. When the adjustment ring is replaced, make certain that the pin on the back of the ring engages the slot in the exposure adjustment mechanism on the camera body and that the spring clip rests against the adjustment ring. The front plate may now be glued back onto the camera body. It will not be necessary to remove the front or exposure adjustment ring again. The front lens may now be removed by carefully prying out the retainer ring inside the exposure adjustment ring. This lens should be marked as the front lens and its orientation in the camera noted so that it may be reinstalled properly.

To remove the rear lens, the camera should be collapsed and the camera back opened. The rear lens may be removed by prying out its retainer ring. Note the orientation of this lens for proper reinstallation.

The pinholes for the camera may be produced by placing aluminum foil over the lens opening and holding it in place with a rubber band around the exposure adjustment ring. Make the pinhole by puncturing the center of the aluminum foil with an appropriate sized object, such as a small wire. When the aluminum foil is straight across the adjustment ring, the image does not fill the full frame of the picture. However, this does not affect the results. If a full-frame picture is desired, first put aluminum foil down into the center of the adjustment ring and then puncture the center of the foil.

In order to make time exposures, cover the photocell with an opaque material, such as black masking tape. Cock the shutter with the shutter cocking lever (marked 3 in Figure 1 of the module). When the shutter release button (2) is pushed, the shutter will open and remain opened until the shutter cocking lever is reset.

When the lenses are replaced properly and the photocell uncovered, the camera is ready for normal use.

Construction of Camera Viewing Screen

The Polaroid camera is converted to a camera obscura by placing a viewing screen in the camera back in place of the film pack. The screen is easily constructed from an empty film pack. The empty film pack consists of a plastic cover plate with a metal backing. The metal parts can be removed, leaving only the plastic insert for the camera back. The opening in this plastic insert may now be covered (glued to the inside) with a translucent material such as the frosted Mylar that is used by draftsmen and artists.

Experiment A-2

Thin converging lens
(5 to 50 cm focal length)
Achromatic converging lens
(approximately the same
focal length as the thin lens above)
Optical bench
Clear incandescent lamp and holder for
the optical bench
Lens holder for the optical bench (2)
White screen with holder
Lens covering (cardboard or similar
material): 1 circular, 1 washer
shaped
Hartl optical disc (or equivalent)
Colli ated light source
Semicircular glass plate
Glass plate shaped like the cross
section of a thin converging lens

Experiment B-1

Thin converging lens (3) (different
focal lengths)
Optical bench
Lighted object (e.g., incandescent lamp)
Lens holder for the optical bench
White screen with holder
Meter stick or centimeter ruler

Experiment C-1

Same as for B-1, plus a compound lens or lens system.

Construction of a Compound Lens System

A compound lens can be constructed by placing 2 lenses in axial alignment in an opaque tube such as cardboard. The effective focal length, f, of such a compound lens is given by

$$\frac{1}{f} = \frac{1}{f_1} + \frac{1}{f_2} - \frac{D}{f_1 f_2}$$

where f_1 and f_2 are the focal lengths of the two lenses and D is the separation between them.

A simple case occurs when two lenses with the same focal length, one a converging lens and the other a diverging lens, are separated by a distance equal to their focal length. The combination produces a converging lens system with a focal length equal to the individual lens focal length. The system is asymmetrical, with one focal point at the surface of the diverging lens and the other twice the lens separation, 2D, away from the converging lens. The lens system recommended by the authors contains two 20-cm focal length lenses, one converging and the other diverging, separated by 20 cm.

Experiment C-2

Same as for A-1, plus one Polaroid type 108 color film pack.

OPTIONAL DEMONSTRATION AIDS

16 mm Sound Films

1. "Lenses" 15 min., B & W. United World Films; available through University of Illinois Film Library.
2. "Fundamentals of Photography: The Basic Camera." B & W, U.S.N.; available through University of Illinois Film Library.
3. "A Picture in the Camera." B & W. Time-Life Films.
4. "The Refraction of Light." Color. Cenco Educational Films.

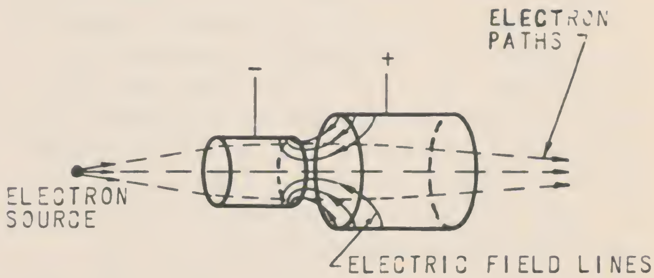
8 mm Film Loops

1. "The Pinhole Camera." No. S-81435, Encyclopedia Britannica Educational Corporation.
2. "Field of View." Gateway Educational Films Ltd.
3. "Models of Reflection and Refraction." Gateway.

Transparencies

1. "A Camera." No. M-6728, Frey Scientific Company.
2. "Real Image." No. M-6727, Frey.
3. "Index of Refraction." No. F-6764, Frey.
4. "Image Formed by a Convex Lens." No. F-6765, Frey.
5. "The Camera." Set of 15, No. WK102, Lansford Publishing Co.

CONTENTS



I INTRODUCTION

This module introduces the student to the components of the CRT and their functions. The emphasis is on physical principles.

Additional topics on which the instructor can add material are thermionic emission; space charge; the physical processes by which the electron kinetic energy is converted to radiation in the phosphor of the screen; secondary emission and its role in preventing the build-up of negative charge on the screen; the nature of aquadag (graphite conductive coating) and its role in preventing build-up of electrons on the screen, keeping stray light from entering the tube, illuminating the screen and reducing contrast, and acting as an electrical shield to reduce the effects of stray electric fields in the tube; the principle of electrostatic focusing (illustrate with the case of two adjacent coaxial cylinders as shown in the next column); and the design of deflection plates. Also stress that the heater should be allowed to warm up before the high voltage is applied to the tube.

II PREREQUISITES

Math requirements are listed in the module.

III TABLE OF CONTENTS OF THE MODULE

Goals for This Module
What You Will Study
The Cathode Ray Tube
Electric Charge
Experiment 1. Electric Charge
Coulomb's Law
Problems and Questions
Electric Fields
Problems and Questions
More About Electric Fields
Experiment 2. Mapping Electric Fields
Treatment of Data
Kinetic and Potential Energy
Electrostatic Deflection in the CRT
Calculations
Experiment 3. Electrostatic Deflection of the CRT Beam
Procedure
Treatment of Data
Calculations
Questions

IV GOALS

The goals of the Cathode Ray Tube module have been included at the beginning of the module.

V DISCUSSION OF ACTIVITIES

There are three laboratory experiments in this module. The placement suggests a sequence of classroom, laboratory, classroom, etc. If this does not conform to the scheduling of classroom and laboratory periods, the instructor has the following choices: (1) select one or more students to perform a laboratory exercise as a demonstration in the classroom with the class observing, offering suggestions, and recording data; (2) schedule laboratories as though the instructional materials for them were placed in an appendix.

Experiment 1. Electric Charge

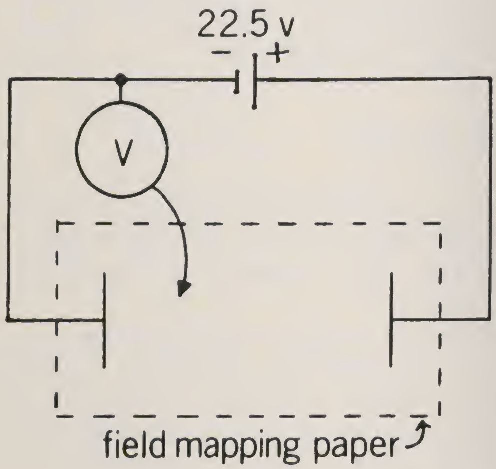
The purpose of this experiment is for the student to test his observations against various hypotheses such as (1) like charges attract and unlike charges repel; (2) like charges repel and unlike charges attract; (3) negative charges repel negative charges and attract positive charges, and positive charges do not interact with positive charges. An alternative approach is to be deductive from the start. Two objects that are rubbed together take on opposite charges. This is a direct consequence of the separation of charge assumption. The fact that all pairs that were electrified by rubbing together attract each other leads to the conclusion that unlike charges attract.

The instructor should try the entire experiment before the laboratory period to see for himself whether or not the observed interactions between charges are consistent, particularly the interactions between electrified rods and the CRT beam, and to become aware of experimental difficulties so that he can better advise students how to proceed.

Experiment 2. Mapping Electric Fields

The purpose of this experiment is for the student to discover and map electric fields of various types.

The instructor may suggest that the student use the CRT as a null detector for field mapping. Alternatively, the instructor can eliminate the potential divider and identify equipotential points as those that give the same voltmeter readings (see experimental arrangement below). The connections are simpler, but the method is likely to be less accurate.



Obviously this experiment can be shortened by simply having students map fewer different electrode configurations. Alternatively, different groups of students can map different field patterns and then share their results with one another.

Experiment 3. Electrostatic Deflection of the CRT Beam

The purpose of this experiment is to have the student observe and measure beam deflection. Both horizontal and vertical deflections are measured.

VI SAMPLE DATA

Experiment 1

It often happens that experiments involving electrostatic charge produce results that are hard to interpret. Damp weather, in particular, is almost

sure to cause trouble. For this reason, data vary. The interaction between the hard rubber rod and Saran Wrap, however, is usually reliable.

Experiment 2

Sample Calculations:

$\Delta \underline{V} = 22.5$ V
$\underline{D} = 5.7$ cm $= 5.7 \times 10^{-2}$ m

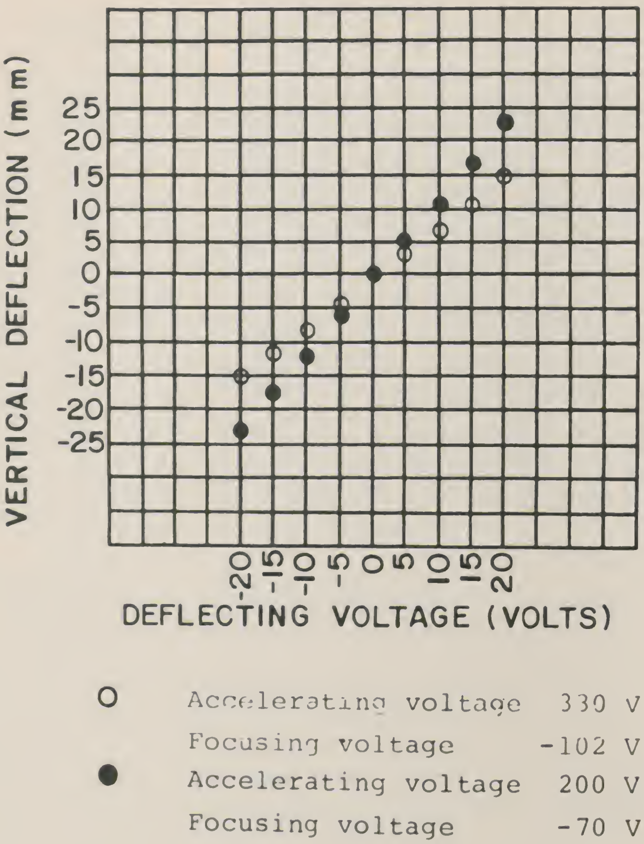
$\underline{V}_2$ (V)	$\underline{V}_1$ (V)	$\underline{d}$ (cm)	$\underline{E}_{av}$ (V/m)	$E=\Delta \underline{V}/\underline{D}$ (V/m)
2.5	0	0.4	6.25×10^2	3.96×10^2
7.0	2.5	1.2	3.75×10^2	
11.2	7.0	1.25	3.36×10^2	
15.0	11.2	1.15	3.3×10^2	
19.0	15.0	1.2	3.3×10^2	
22.5	19.0	0.5	7.0×10^2	

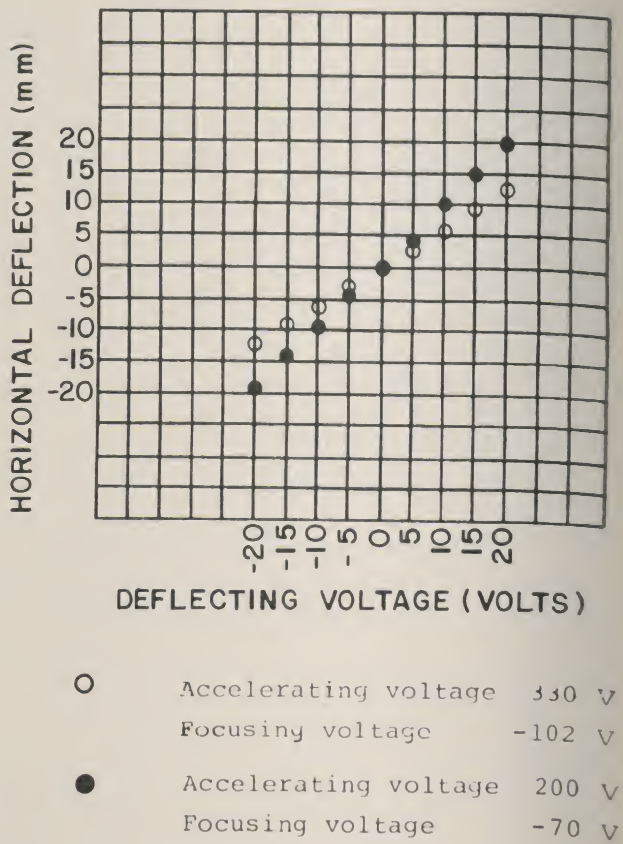
The nonuniformity of $\underline{E}_{av}$ is due to the finite extent of the plates.

Experiment 3

2. The curves are straight lines.
3. Increasing the accelerating voltage decreases the deflections and therefore the slope of the line.
4. The vertical deflections are larger because the vertical plates are further from the screen than the horizontal plates.

Typical data which can be obtained by students using the Berkeley Laboratory equipment are shown on the next page.





VII ANSWERS TO QUESTIONS AND SOLUTIONS TO PROBLEMS

The problems and questions in this module are an important part of the module and should be discussed in class, if possible.

Page 9

1. Electrostatic induction.
2. Answers vary.

Page 11

1. (a) doubled; (b) quadrupled; (c) becomes 9 times as large.
2. 72 N attractive.
3. 2.3×10^{-8} N attractive.
4. (d).
5. (a).
6. (a) 0.63 N to the right; (b) 2.4 N to the right.
7. (1) 1.7 N; (2) down and right.

Page 13

1. Electric intensity is a vector which at any point is equal to the force on a positive charge placed at that point divided by the magnitude of the charge. Electric field strength means the same as electric intensity.
2. The direction of the force on a positive charge.
3. (a) 2.5×10^3 N/C; (b) 1 N.
4. 0.033 N.
5. 5.8×10^{11} N/C radially outward.
6. 1.1×10^4 N/C toward the negative charge.

Page 23, Group 1

1. It is fairly constant except close to the plates.
2. In the region generally assumed to be uniform there is about 15% variation in magnitude.

Page 23, Group 2

1. Proton, 1 eV; alpha particle, 2 eV.
2. (a) 5.9×10^5 m/s; (b) 1.38×10^4 m/s.
3. A positively charged particle will move toward the 8-V line. An electron will move toward the 12-V line.
4. 5.3×10^{-17} J; 3.3×10^2 eV.
5. (a) The kinetic energy of an electron leaving the electron gun in a color set is twice as great.
   (b) The electron's velocity in the color set is greater by a factor of $\sqrt{2}$.
6. For a color set, force $F = 3.84 \times 10^{-13}$ N; for a black and white set, $F = 1.92 \times 10^{-13}$ N. Note: Error in text. Should read "1.0 cm long."

Page 24

1. (a) 10^7 m/s, 2.24×10^7 mi/hr;
   (b) 285 V.
2. $L = 2.0$ cm.
3. $D = 1.0$ cm.
4. 8.0 cm.
5. 2×10^{-9} s.
6. Time = distance/velocity

$$= \frac{8.0 \times 10^{-2}\ \text{m}}{10^7\ \text{m/s}}$$
$$= 8.0 \times 10^{-9}\ \text{s}$$

There are 20 intervals of 4×10^{-10} s.

$$\text{Time} = 20 \times 4 \times 10^{-10}\ \text{s}$$
$$= 8.0 \times 10^{-9}\ \text{s}$$

Calculations

Note: This should be done as a classroom exercise. If you feel that the exercise is too long and demanding to hold the interest of your students, you can reduce the amount of calculation in the following way: When the students reach Steps 4 and 5, suggest that they calculate V_y and S_y only for the total time the electron spends in the region between the plates, that is, $t = 20 \times 10^{-10}$ seconds. A comparison with $S_{measured}$ at this point is still possible, but obviously Table II would be reduced to a single row of entries.

Page 26

4. and 5.

t (s)	V_y (m/s)	S_y (m)	$S_{measured}$ (m)
4×10^{-10}	7.05×10^5	0.141×10^{-3}	0.15×10^{-3}
8×10^{-10}	1.41×10^6	0.563×10^{-3}	0.55×10^{-3}
12×10^{-10}	2.1×10^6	1.27×10^{-3}	1.25×10^{-3}
16×10^{-10}	2.8×10^6	2.25×10^{-3}	2.25×10^{-3}
20×10^{-10}	3.52×10^6	3.52×10^{-3}	3.50×10^{-3}

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1. $\underline{E} = \frac{\underline{V}}{\underline{D}} = \frac{100\text{ V}}{1 \times 10^{-2}\text{ m}} = 10^4\text{ V/m}$

2. $\underline{F} = \underline{qE}$
$= (1.6 \times 10^{-19})\ (10^4)\text{ N}$
$= 1.6 \times 10^{-15}\text{ N}$

3. $\underline{a}_y = \frac{\underline{F}_y}{\underline{m}} = \frac{1.6 \times 10^{-15}\text{ N}}{9.11 \times 10^{-31}\text{ kg}}$
$= 1.76 \times 10^{15}\text{ m/s}^2$

4. and 5.
See table at the bottom of the preceding page.

6. $\underline{M} = \underline{L} + \underline{S}_y = (\underline{V}_y\underline{d}/\underline{V}_x) + \underline{S}_y$
$= (3.52 \times 10^6 \times 8.0 \times 10^{-2})/10^7 + 3.52 \times 10^{-3}$
$= 0.0317\text{ m}$

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Note: One of the objectives of these questions is to emphasize that the horizontal and vertical motions may be calculated independently.

1. $\underline{S}_y$ and $\underline{S}_{measured}$ compare well. All errors are within the accuracy of the experimental measurements.

2. $\underline{S}_y = (1/2)\underline{at}^2$
$= (1/2)(9.8)(2 \times 10^{-9})^2$
$= 1.96 \times 10^{-17}$ m (insignificant)

3. $\underline{S}_y = 3.52 \times 10^{-3}\text{ m}$
$\underline{V}_y = 3.52 \times 10^6\text{ m/s}$

4. Calculated value: $\underline{M} = \underline{L} + \underline{S}_y$
$= 0.0317\text{ m}$
Measured value: $\underline{M} = 0.033\text{ m}$

5. Sensitivity = 0.0317 m/100 V
$= 3.17 \times 10^{-4}\text{ m/V}$

6. $\underline{V}_x = \underline{\ell}/\underline{t}$ and $\underline{V}_y = \underline{a}_y\underline{t}$
$\underline{S}_y = (1/2)\underline{a}_y\underline{t}^2$
$\text{Tan }\theta = \frac{\underline{L}}{\underline{D}} = \frac{\underline{V}_y}{\underline{V}_x} = \frac{\underline{a}_y\underline{t}}{\underline{\ell}/\underline{t}} = \frac{\underline{a}_y\underline{t}^2}{\underline{\ell}} = \frac{\underline{S}_y}{\underline{\ell}/2}$

or

$\frac{\underline{S}_y}{\tan\theta} = \underline{\ell}/2$ (q.e.d.)

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1. If the accelerating voltage is decreased, the electron spends more time between the deflection plates and in traveling from plates to screen. This makes the deflection greater.
2. Assumptions made in the calculations that can lead to differences between calculated and observed deflections: (1) That the field exists only between the plates and is uniform there; (2) That the plates are flat when they are actually flared.
3. (d). This answer can be obtained in two ways: (1) From an examination of experimental results; (2) By reasoning: (a) the distance an electron is deflected for a given deflecting force depends on the square of the time it spends in the deflecting field; (b) this time is inversely proportional to the horizontal velocity; (c) the square of the horizontal velocity is proportional to the kinetic energy just before deflection; (d) this kinetic energy is equal to the potential energy before acceleration, which in turn is proportional to the accelerating voltage.
4. (a) K.E. $= \underline{qV} = 1.6 \times 10^{-19} \times 500$
$= 8 \times 10^{-17}\text{ J}$

K.E. $= \frac{1}{2}\underline{mv}^2 \quad \underline{v} = \sqrt{\frac{2\text{K.E.}}{\underline{m}}}$

$\underline{v} = \sqrt{\frac{2 \times 8 \times 10^{-17}}{9.11 \times 10^{-31}}}$
$= 1.32 \times 10^7\text{ m/s}$

(b) $\Delta V = 100\ V - 500\ V = -400\ V$

$q\Delta V = -1.6 \times 10^{-19} \times 400$
$= -6.4 \times 10^{-17}\ J$

Net kinetic energy carried by electron inside anode #1 is

$8 \times 10^{-17} - 6.4 \times 10^{-17}$
$= 1.6 \times 10^{-17}\ J$

$$v = \sqrt{\frac{2 \times 1.6 \times 10^{-17}}{9.11 \times 10^{-31}}}$$

$= 5.93 \times 10^{6}\ m/s$

(c) K.E. $= 8 \times 10^{-17}\ J$

$v = 1.32 \times 10^{7}\ m/s$

(d) Its speed does not change because the electric field force inside the anode is zero.

VIII POST TESTS

Test 1

1. An electrically charged rod is brought near an electrically neutral piece of aluminum foil suspended by a nylon thread.
   (a) Describe and explain what you expect to observe.
   (b) What happens if the rod is allowed to touch the foil?
   (c) Two point charges are observed to repel each other. We can conclude that the charges are: (1) both negative; (2) both positive; (3) unlike; (4) like.
   (d) Given the CRT, how can you determine the type of charge placed on an object such as a rubber rod?
2. Two small spheres each carrying 5 μC of negative charge are placed 0.2 m apart. Along the line connecting them a third small sphere carrying 0.6 μC of positive charge is placed a distance of 0.05 m away from one of the negative charges.
   (a) Draw a sketch showing the charge arrangement and the force vectors.
   (b) Apply Coulomb's law to calculate the net or resultant electric force acting on the positive charge. (The constant in the Coulomb's law equation is $K = 9 \times 10^{9}$ SI units.)
3. (a) How is electric potential related to: (1) electric potential energy; (2) voltage?
   (b) How is electric field strength or intensity related to: (1) electric force; (2) voltage?
   (c) An electron of mass m, charge q, and initial velocity zero is subjected to an accelerating voltage of V volts. (1) In this situation, energy is converted from one form to another. What are these forms? (2) Use the principle of conservation of energy to show mathematically how to find the final velocity of the electron.
4. (a) A positive test charge of 0.2 μC is moved a path length of d m along an equipotential surface of potential 30 V. The work done on the test charge is (check one): (1) $2d \times 30$ J; (2) $(2 \times 30)/d$ J; (3) zero; (4) $-2d \times 30$ J.
   (b) The same test charge is moved to another equipotential surface of potential 80 V. What is the work done on the test charge?
5. (a) An electric field line is (check one): (1) Parallel to the direction of the electric force; (2) Perpendicular to the direction of the electric force; (3) Parallel to the equipotential surface; (4) Perpendicular to the potential difference.

(b) Why can two different equipotential surfaces never cross?
(c) Why can two different field lines never cross?
(d) Sketch several field lines and equipotential surfaces associated with a charged cylindrical conductor. Assume you are looking at an endface of the cylinder.
(e) The electric field strength or intensity inside a charged hollow closed metal cylinder is always zero. Can you think of a common practical application of this physical fact?

6. An electron (charge $q = 1.6 \times 10^{-19}$ C, mass $m = 9.11 \times 10^{-31}$ kg) enters the space midway between a pair of vertical (Y) deflection plates with a horizontal velocity equal to 1.18×10^7 m/s. The length ℓ of the plates in the horizontal direction is 0.04 m, the plate separation D is 0.01 m, and the applied vertical deflection voltage is 40 V.
(a) Calculate the deflecting force F_y acting on the electron.
(b) Use Newton's law of motion to show that the resulting acceleration a_y must be: (1) 2.8×10^9 m/s^2; (2) 7.0×10^{14} m/s^2; (3) 5.2×10^6 m/s^2; (4) 5.2×10^{-4} m/s^2.
(c) How long does it take the electron to travel the length ℓ of the plates in the horizontal direction? (1) 3.4×10^{-9} s; (2) 1.7×10^{-5} s; (3) 5.6×10^{-6} s; (4) 8.5×10^{-2} s.
(d) Verify that the deflection in the Y direction after traveling the length of the plates is: (1) 2.15×10^{-5} m; (2) 8.4×10^{-4} m; (3) 8.4×10^{-3} m; (4) 4.05×10^{-3} m.

Test 2

1. (a) An experimenter holds a charged rod near (but not touching) a piece of aluminum foil suspended by a fine nylon thread. Draw a sketch showing the charge distribution on the rod and on the foil.
(b) She allows the rod to briefly touch the foil. Draw a sketch showing the charge distribution on the rod and foil after touching.
(c) What happens to the charge placed on the aluminum foil if she brings it in contact with: (1) another piece of aluminum foil; (2) her finger?
(d) She moves the charged rod (assume it is a negative charge) rapidly toward a deflection plate terminal of a CRT (without touching) and then withdraws it rapidly. Describe what you expect to see on the CRT screen for the two cases and give reasons for the behavior of the electron beam.

2. (a) A positive point charge of 50 μC is situated at $x = 0$. Calculate the electric field strength or intensity E at $x = 0.05$ m.
(b) A negative point charge of equal size is placed at $x = 0.10$ m. The value of the electric field strength E at $x = 0.05$ m is changed to: (1) 5.4×10^4 N/C; (2) 3.6×10^8 N/C; (3) -1.8×10^8 N/C; (4) zero.
(c) What is the size and direction of the electric force (in newtons) acting on a positive test charge of 3 μC placed midway between the two point charges?

3. (a) The electric field strength or intensity can be expressed in two equivalent forms of SI units. What are they?
(b) Is any electrical work being done if a test charge is moved along: (1) an equipotential surface; (2) a field line?
(c) Why must equipotential surfaces

and field lines be at right angles to one another?

4. (a) Draw a diagram showing several field lines and equipotential surfaces in the space between two parallel plate conductors.
   (b) If the distance between the plates is 10^{-2} m and the voltage is 100 V, what is the electric field strength or intensity: (1) at the positively charged plate; (2) at the negatively charged plate; (3) midway between the plates?
   (c) Assume the electric potential at the negative plate is zero. What is the electric potential: (1) at the positive plate; (2) midway between the plates?
   (d) The size of the electric field strength or intensity will be increased by (check one): (1) increasing the plate area; (2) decreasing the voltage; (3) increasing the plate separation; (4) decreasing the plate separation.
5. Electrons are accelerated in a CRT without deflection through a potential difference of 300 V. If each electron carries a charge of 1.6 x 10^{-19} C and is assumed to have initial velocity equal to zero, what is its:
   (a) Potential energy (in joules) at the cathode?
   (b) Potential energy at the final anode?
   (c) Kinetic energy at the cathode?
   (d) Kinetic energy at the final anode?
   (e) Kinetic energy just before impact on the screen?
6. (a) Draw a side-view sketch of a CRT showing the envelope of the tube, cathode, anode, a pair of vertical deflection plates, and the path of a vertically deflected electron beam. Describe the shape of the path between the deflection plates and beyond the deflection plates.
   (b) A CRT having a vertical deflection plate separation D = 0.01 m is operated with a deflection voltage V = 600 V. The electron's charge-to-mass ratio is known to be 1.8 x 10^{11} C/kg. Show that the vertical acceleration a_y is: (1) 5.56 x 10^{22} m/s^2; (2) 7.90 x 10^{22} m/s^2; (3) 3.33 x 10^{-11} m/s^2; (4) 1.08 x 10^{16} m/s^2.
   (c) If the time of flight of the electron through the deflection plates is t = 10^{-10} s, the vertical deflection at the end of the plates is: (1) 4.32 x 10^{-3} m; (2) 1.08 x 10^{-2} m; (3) 8.64 x 10^{-4} m; (4) 2.16 x 10^{-3} m.
   (d) In your final CRT experiment you measured deflections of the electron beam. You were able to conclude that vertical as well as horizontal deflections (check one): (1) did not change with change in deflection voltage; (2) did not change with change in forward acceleration of the beam; (3) increased linearly with increase in deflection voltage; (4) increased nonlinearly with increase in deflection voltage.

Test 3

1. A mad scientist asserts that the idea that there are two different kinds of electrical charge, positive and negative, is all wrong. He insists that there is only one kind of charge, and all charges behave like all other charges when they interact with each other. Referring only to phenomena that you have observed and could reproduce in a laboratory, how would you refute his arguments?
2. Are electrical forces attractive or repulsive?
3. Define in words:
   (a) The concept of the electric field in terms of qualitative

observations.
(b) Electric intensity in terms of quantitative procedures and measurements.
(c) Potential difference.

4. What are the SI units for each of the following quantities?
(a) length (e) force
(b) time (f) energy
(c) mass (g) potential difference
(d) electric charge (h) electric intensity

5. Write down the equation that expresses Coulomb's law and state the meaning of each symbol in the equation.

6. A charged water droplet is at rest under the influence of gravity. The weight of the droplet is 2 x 10^{-4} N and its charge is -4 μC. What is the magnitude and direction of the electric intensity that prevents the droplet from falling?

7. (a) Why is it that no two electric field lines can intersect?
(b) Why is it that no two equipotential surfaces can intersect?
(c) Why does every field line intersect every equipotential surface at right angles?

8. A charged particle enters a uniform electric field at a point x = 0, y = 0, with its initial velocity in the x direction and the field in the y direction. After 1 s, the particle is at the point x = 1 m, y = 1 m. Where will the particle be at t = 2 seconds?

9. An electron starts from rest and falls through a potential difference of 6 V. What is its final kinetic energy in joules? In electron volts?

10. Show that you know what you must do—that is, what knobs you must turn and what readings you must take—in order to determine the graph of deflection versus deflecting voltage using the apparatus of Experiment 3 in the Cathode Ray Tube module. You may exhibit this knowledge by any one of these three methods, depending on your instructor's wishes:
(a) Write a paragraph.
(b) Describe the procedure orally.
(c) Demonstrate using the apparatus.

ANSWERS TO POST-TESTS

Test 1

1. (c) (4).
2. (b) 9.6 N.
3. (a) (1) potential energy per unit charge; (2) potential difference.
(b) (1) $E = F/q$; (2) $E = \Delta V/d$.
(c) (1) Electric potential energy to kinetic energy. (2) $(1/2)mv^2 = qV$; then $v = \sqrt{2qV/m}$.
4. (a) (3).
(b) 10^{-5} J.
5. (a) (1).
(e) Electric shielding.
6. (a) 6.4 x 10^{-16} N.
(b) (2).
(c) (1).
(d) (4).

Test 2

1. (c) (1) Charge is shared; (2) shared to the extent that it is grounded.
2. (a) 1.8 x 10^8 N/C.
(b) (2).
(c) 1.08 X 10^3 N; directed to the right.
3. (a) Newtons/coulomb and volts/meter.
(b) (1) no; (2) yes.
4. (b) (1) 10^4 V/m; (2) same as (1); (3) same as (1).
(c) (1) 100 V; (2) 50 V.
(d) (4).
5. (a) 4.8 x 10^{-17} J.
(b) Zero.
(c) Zero.
(d) 4.8 x 10^{-17} J.
(e) 4.8 x 10^{-17} J.
6. (b) (4).
(c) (3).
(d) (3).

Test 3

1. Answers vary.
2. Like charges attract; unlike charges repel.
4. (a) meters (b) seconds (c) kilograms (d) coulombs (e) newtons (f) joules (g) volts (h) newtons/coulomb or volts/meter
5. $\underline{F} = (\underline{KQ_1Q_2})/\underline{r}^2$.
6. $\underline{E} = \underline{mg}/\underline{q} = (2 \times 10^{-4})(4 \times 10^{-6})$ $= 50$ N/C down.
8. $\underline{x} = 2$ m; $\underline{y} = 4$ m.
9. $\underline{KE} = 6 \text{ eV} = 6 \times 1.6 \times 10^{-19}$ $= 9.6 \times 10^{-19}$ J.
10. Answers vary.

IX LIST OF APPARATUS

Experiment 1

Hard rubber rod
Glass rod
Silk cloth
Plastic wrapping such as Saran Wrap
Silk or nylon thread
Aluminum foil
CRT assembly including power supply (Thornton Associates)

Note. Instructors who use the Berkeley Physics CRT and power supply should connect the apparatus as shown on the next page. This set-up will give the desired results, but is electrically not as safe and not as convenient to operate as the design offered by Thornton Associates. If the bright spot doesn't appear on the screen, try touching the high-voltage (+) terminal of the power supply with the flat antenna-type leads which are connected to the deflection plates. To obtain and hold the spot, the deflection plates (especially the pair closest to the second anode) must be brought to the same potential as the second anode. To avoid danger of electric shock, do not connect the antenna leads permanently; in this experiment the deflection plate terminals must be readily accessible for making contact with charged rods.

Electrostatic deflection of the beam spot using charged rods works better if the bleeder resistor at the end of each antenna lead is removed.

Experiment 2

Potentiometer
DC voltmeter (range 0 to 25 V)
22½-V battery or comparable power supply
Field mapping paper (4 sheets)
Mounting board
Metal clamps (4)
Conducting paint
Small brush

Note. The silver conducting paint may take twenty minutes to half an hour to dry. The students should be advised to draw their electrode configurations immediately on entering the laboratory. Be sure to have plenty of paper and paint on hand.

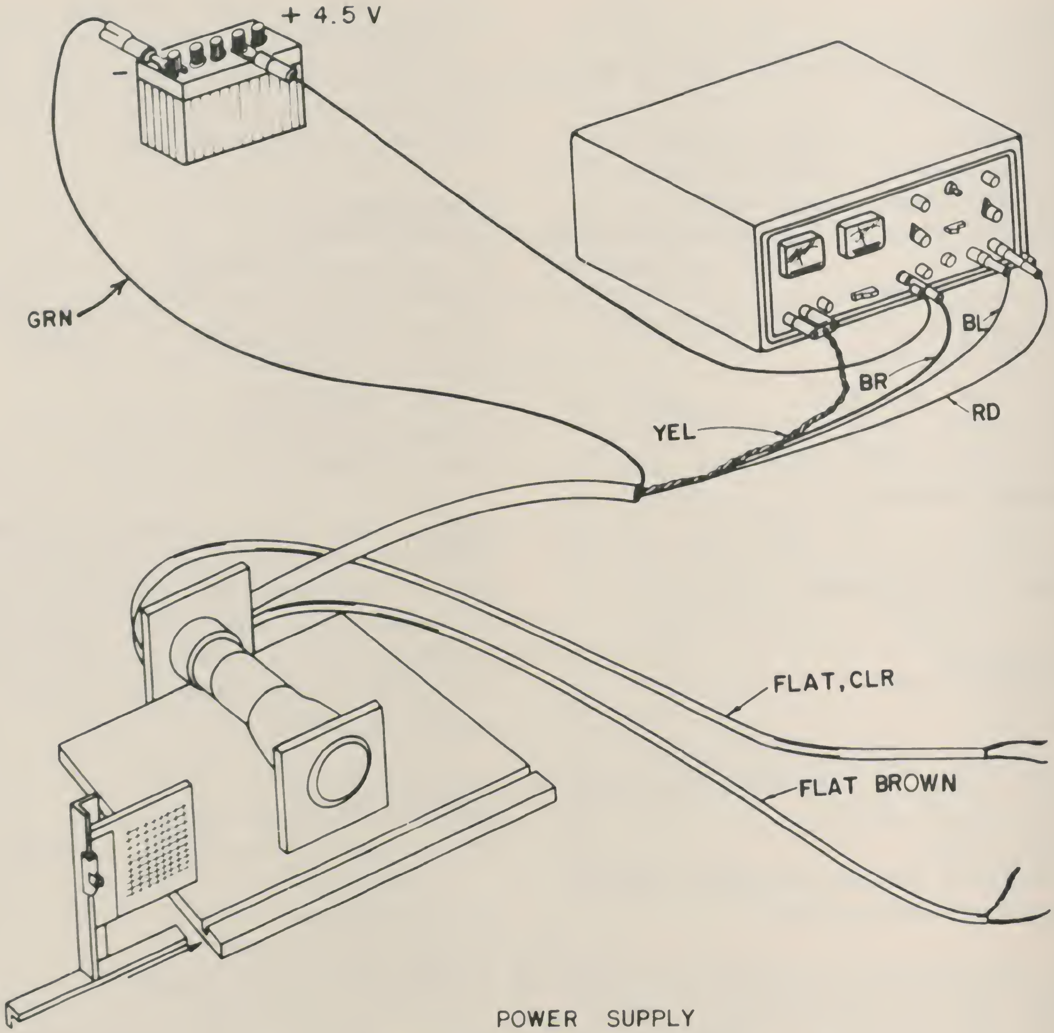
Experiment 3

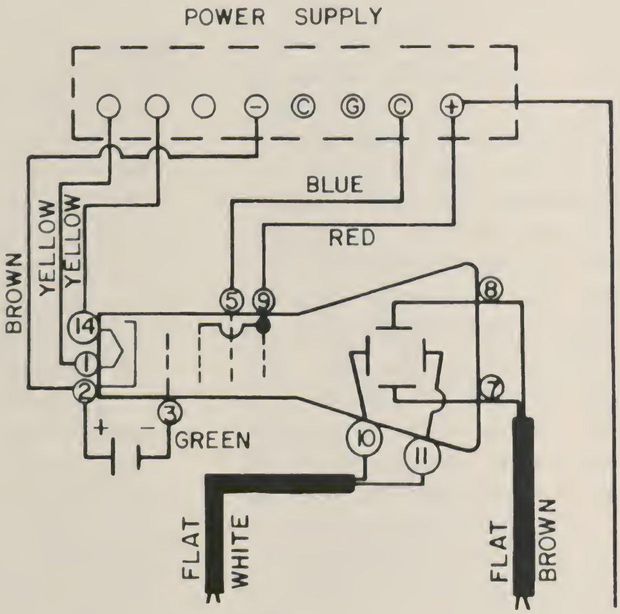
CRT with power supply
DC voltmeter—preferably VTVM, max range 30 V
Grid holder
Plastic grids (2)
Supply of graph paper

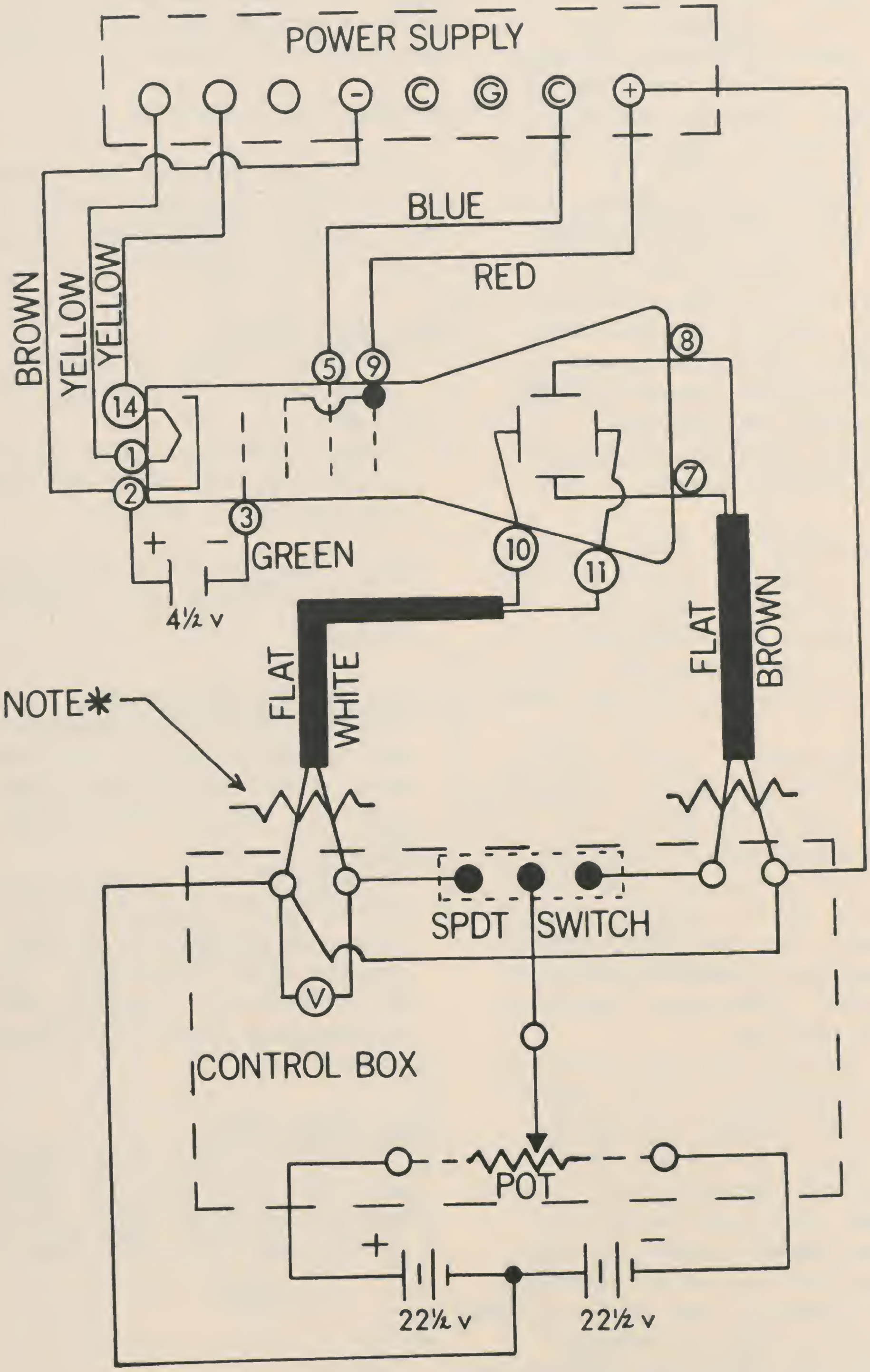
Note. The Thornton apparatus for the CRT module was not available for testing at the time of writing, so references here are limited to the Berkeley Laboratory equipment.

For Experiment 3 this should be wired as it was for Experiment 1, except this time the flat antenna-type leads from the deflection plates are connected to a potentiometer control box and to the high-voltage positive terminal labeled "+" on the Heathkit power supply (see circuit diagram).

The potentiometer control box is a self-built unit containing a 25-kΩ pot which is connected to banana plug terminals and an SPDT toggle switch as shown. Deflection voltage is supplied by a 45-V battery. The pot is connected to the battery in such a way that the


+ 4.5 V
-
GRN
YEL
BR
BL
RD
FLAT, CLR
FLAT BROWN


POWER SUPPLY
BROWN
YELLOW
YELLOW
BLUE
RED
GREEN
FLAT WHITE
FLAT BROWN



47 K Ω RESISTORS ALREADY SOLDERED TO BANANA PLUGS.

deflection voltage can be varied from +22.5 V to -22.5 V. By means of a toggle switch, the deflection voltage can be applied to one or the other pair of deflection plates. Both pairs are maintained at the potential of the second anode.

The high-voltage supply (terminals COMMON and +) can be varied between 0 and 400 V. It supplies the accelerating voltage for the electron beam. Beam focusing is accomplished by adjusting both controls marked "-" and "+" on the Heathkit power supply. The voltage across the terminals COMMON and - does most of the focusing and can be varied between 0 and -180 V.

The fixed potential of -4.5 V on the first grid relative to the cathode repels electrons back toward the cathode. It limits electron beam intensity to a value which will not burn a hole in the screen if the beam is stationary.

Connect the voltmeter last. Set it to a 25-V or higher scale, connect one lead, and, while watching the meter needle, momentarily touch the other lead to its point of connection in the circuit. If the needle starts to move off scale to the left, reverse the meter leads and connect the meter into the circuit. The meter measures the deflection voltage.

To compare calculations and measurements, it is necessary to know which set of deflecting plates is nearer the screen. Pins 7 and 8 of the CRT connect to the deflecting plates closer to the cathode, and pins 10 and 11 connect to the plates closer to the screen. Which set is the horizontal and which the vertical deflection plates depends on how the tube is turned.

Warning: Do not touch the deflection plate terminals, as you might have in Experiment 1. This time they are connected to the high-voltage (+) terminal power supply and may be "hot"!

Note. The tube and grid holder assemblies can be built more cheaply from the shop drawings included here.

OPTIONAL DEMONSTRATION AIDS

The following films and slides are relevant instructional aids, which can be used or not at the discretion of the instructor.

8-mm Film Loops

1. "Coulomb's Law"; S81325.
2. "Historical Introduction to CRT"; S81496.
3. "Rubber Membrane Model of Fields in CRT and Ball Bearings Showing Trajectories"; S81510.

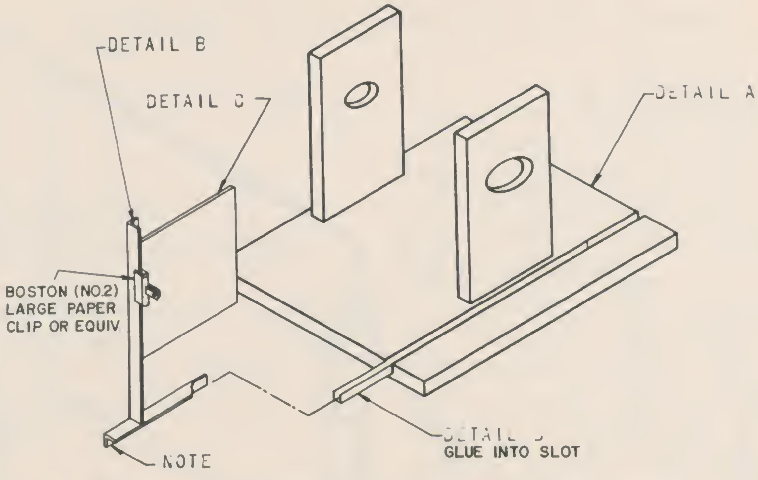
(All: Encyclopedia Britannica Corp., 425 N. Michigan Ave., Chicago, Ill. 60611.)

Slides and Transparencies

1. "Cathode Ray Oscilloscope," 18 slides and written theory; Lesson-Pac #402. American Educational Systems, P.O. Box 308, N. Wilbraham, MA 01067.
2. "Physics Diazo Transparencies." Set 18 shows gravitational acceleration and projectile motion. 1 base drawing and 5 overlays. Catalogue No. 306105-18. Keuffel and Esser, 20 Whippany Road, Morristown, NJ 07960.

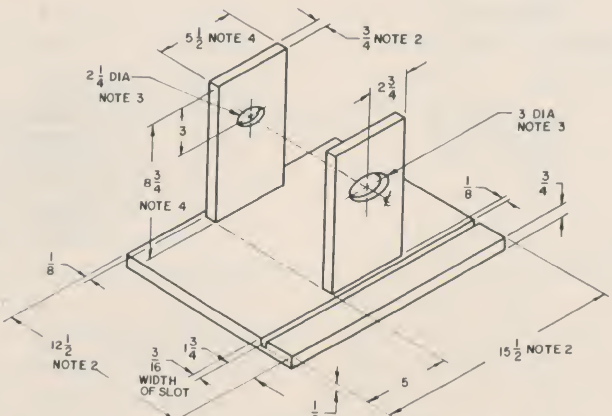
16-mm Sound Film

1. "Coulomb's Law," Eric Rogers. 30 minutes; Catalogue No. 0403. Modern Learning Aids, 1212 Avenue of the Americas, New York, NY 10036.



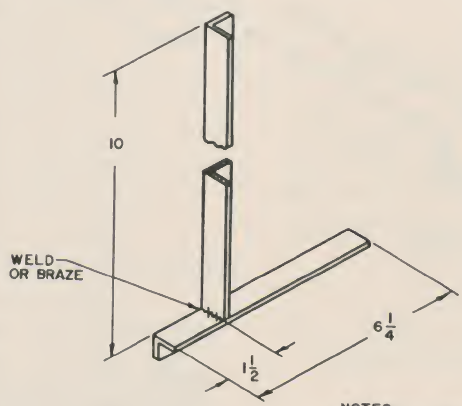
NOTE: SLIDE UPRIGHT POST INTO SLOT OF THE BASE

CRT HOLDER-ASSEM



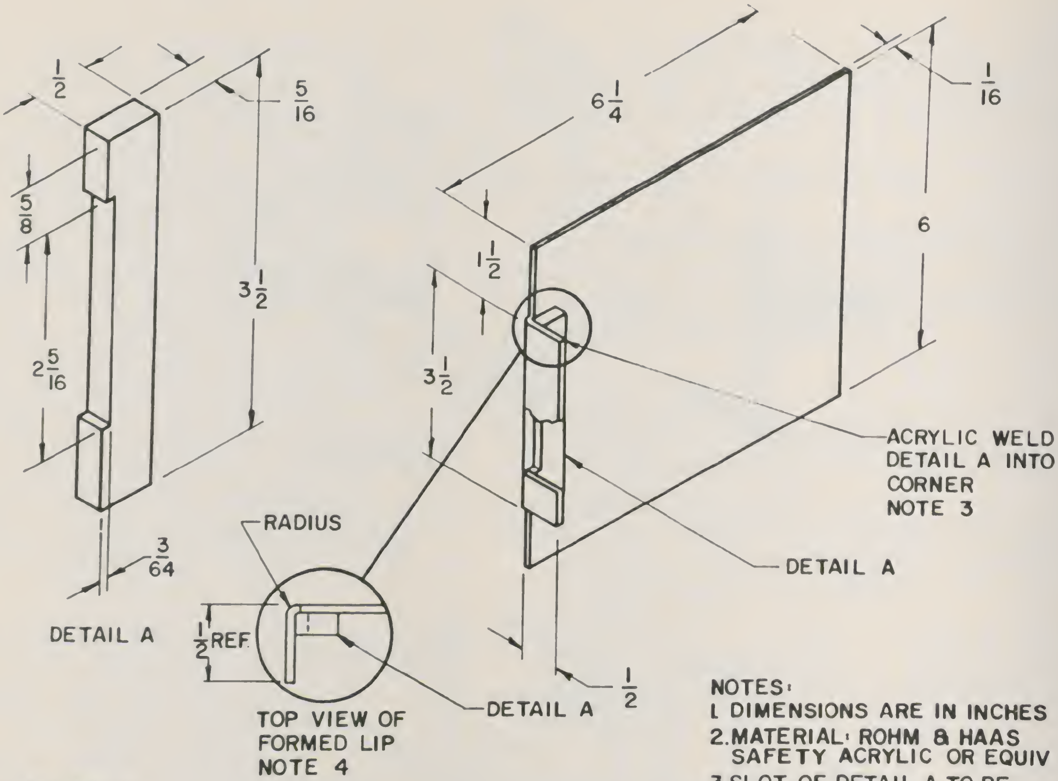
DETAIL A
BASE-C R T HOLDER

NOTES:
1 DIMENSIONS ARE IN INCHES.
2 MATERIAL 3/4 PLYWOOD OR EQUIV.
3 HOLES TO BE IN LINE WITHIN 1/32.
4 GLUE & SCREW INTO POSITION



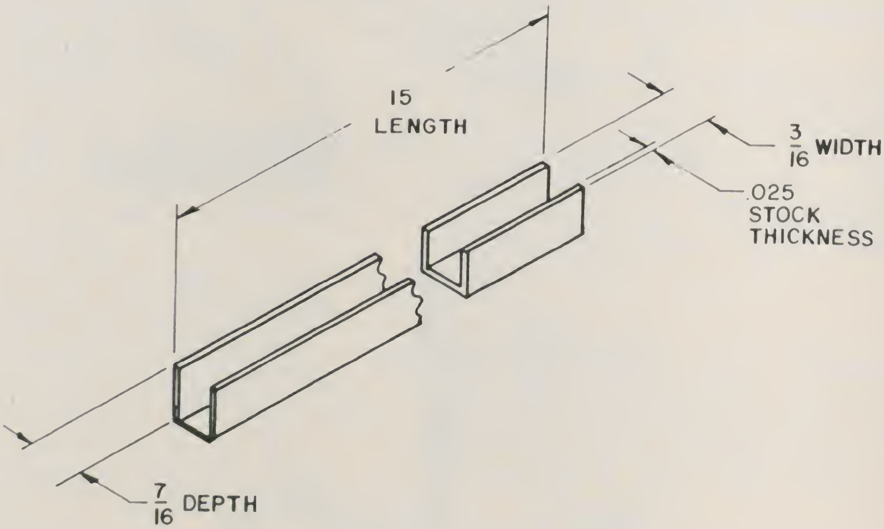
DETAIL B
UPRIGHT POST-CRT

NOTES:
1. MATERIAL: ANGLE IRON $\frac{1}{8} \times \frac{5}{8} \times \frac{5}{8}$
2. FINISH: PAINT-COLOR OPTIONAL.
3. DIMENSIONS ARE IN INCHES.



NOTES:
1. DIMENSIONS ARE IN INCHES
2. MATERIAL: ROHM & HAAS SAFETY ACRYLIC OR EQUIV
3. SLOT OF DETAIL A TO BE FREE OF ADHESIVE.
4 HEAT PART TO FORM LIP

DETAIL C
GRID HOLDER



NOTES:
1. ALL DIMENSION ARE IN INCHES.
2. MATERIAL: COPPER SHIM STOCK.

DETAIL D
TRACK

CONTENTS

I INTRODUCTION

The Cloud Chamber is a short module concerned with observations of alpha and beta tracks by the use of a diffusion cloud chamber. The apparatus is simple, small, and inexpensive. Dry ice and alcohol are the only materials that must be obtained in addition to what is available with the module. A complete list of apparatus and materials appears in Section VIII.

The physics that is discussed is mostly that of vapors, supercooling, condensation, and related topics. The physical principles involved in radioactivity and the ionization of atoms are also discussed to some extent, but are not emphasized.

Laboratory exercises constitute the basis for the ideas discussed. Theoretical discussions are closely woven together with laboratory exercises, but all instructions for activities are set off in such a way that the student will have no difficulty identifying them.

At various points in the module "thought questions" are given, to stimulate review and further thought. Numerical problems are not emphasized.

Since the module is very short, it will probably require no more than two weeks. In some cases, one week might be adequate. The module is written so that a student should be able to proceed with little detailed lecturing or other help from the teacher. Such help is, of course, not ruled out. The module lends itself nicely to being taught by the Personalized System of Instruction (PSI) or other forms of self-paced learning.

A special word should be said about the "thought questions." They cannot be answered purely on the basis of what is said in the text. They are meant as stimuli for <u>further</u> thought, combining what the students have learned with common sense and what they already know from previous experience. Probably the best way to use the thought questions would be as the basis for class discussions or discussions involving small clusters of students. As such, they can serve very well both as a review of material covered in the text and also as stimuli for thinking of the relevance of the various ideas to other situations.

The "Suggestions for Further Study" are just that. Detailed instructions are given for one of these experiments. The others are more open-ended and no promise is made that the student will be able to make the indicated observations. They are more in the nature of research projects that might take considerable time.

II SPECIAL PREREQUISITES

There are no special prerequisites for this module, except that for the Physics of Technology series as a whole: high school algebra.

III TABLE OF CONTENTS OF THE CLOUD CHAMBER MODULE

SECTION A.

How a Diffusion Cloud Chamber Works
Introduction

IV GOALS OF THE CLOUD CHAMBER MODULE

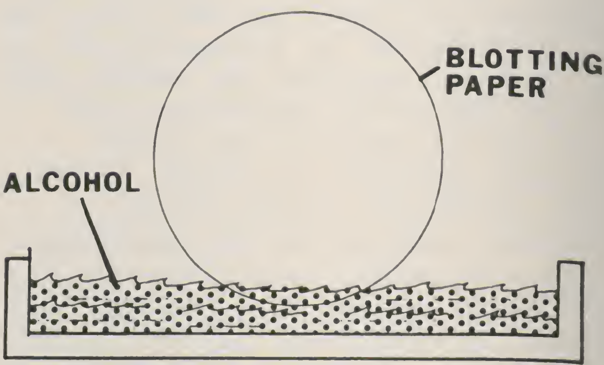
As you work through this module you will learn:

1. How to detect moving charged particles.
2. How to identify the charged particles which you detect.
3. The effects of particle mass and charge on the formation of tracks in the cloud chamber.
4. How to describe the processes of evaporation and condensation in simple terms.
5. The effect of cooling a vapor to a temperature lower than its normal condensation temperature.
6. The effect of cooling a liquid to a temperature lower than its normal freezing temperature.
7. The relationship between vapor condensation and a variety of naturally occuring phenomena, such as the formation of frost, dew, and fog.
8. How to measure the rate at which charged particles are given off by a radioactive material.

V DISCUSSION OF ACTIVITIES

<u>Experiment A-1</u>. <u>Operating a Cloud Chamber</u>: <u>Radium Tracks</u>

1. The slab of dry ice should be nearly level and it should be flat where the chamber sits. The dry ice can be sawed into slabs with a hand saw or band saw. Thickness is not critical. A towel wrapped around the exposed part of the dry ice will prolong its life. But the chamber must sit directly on the dry ice.
2. The students should be urged to handle the sources carefully, not touching them against anything.
3. A good way to moisten the band of blotting paper is to remove it and rotate it (in a vertical plane), dipping only a small part in the alcohol.



The alcohol on the blotting paper

will need to be replenished after about 30 minutes of operation.

4. Tracks are visible only in the lower part of the chamber (perhaps up to 1 cm depth). At the very beginning the limit is even lower. Temperature measurements should vary from about -10°C near the bottom to +10 to 15°C near the top.

Experiment A-3. Solidification of Sodium Acetate

The first process is dissolving the sodium acetate in a small amount of water. After the mixture re-solidifies, the water is still mixed with the solid sodium acetate and the mixture can be used over and over. That is, it will again liquify when it is heated.

Experiment B-1. A Closer Look at Cloud Chamber Tracks

1. Barriers should be small, perhaps 1 x 2 cm, bent at right angles. Larger barriers, especially of metal, upset the temperature distribution so that tracks may not be visible near them. Also, alcohol collects on the bottom and eventually dampens the barriers. This will prevent alphas from penetrating even the onion skin paper barrier. Some teachers might prefer to omit the absorption experiment here, since it is also done later (with a different source).
2. It should be possible to observe short alpha tracks beyond the onion skin paper barrier.

Experiment B-2. Specific Ionization and Scattering

Beta tracks are difficult for most people to see. A small magnifying glass might be helpful. Careful viewing will show the droplets like drops of water in a rainstorm. The beta tracks are thread-like concentrations in the "rain." They are nearly always curved (because of scattering of the beta particles) and they usually change their shapes rapidly because of currents in the vapor.

Experiment B-3. Radiation Absorption

Beta tracks should be visible beyond any of the barriers, showing that they have much greater penetrating ability than alpha particles.

Experiment B-4. Measurement of Source Activity

1. The barrier must be small, in order to minimize the effect on temperature distribution.
2. Results of this experiment are generally not precise, because of errors in measuring the small distances and also because of statistical fluctuations in the number of tracks counted. But the idea of the experiment is instructive and the values obtained should be at least of the correct order of magnitude.

Sample data and calculations:

$\underline{d}$ = 0.26 cm
$\underline{D}$ = 2.3 cm
$\underline{n}$ = 12 counts in 10 minutes
= 1.2/min

Using these data in the formula, $\underline{R}$ is 1,480/min or 25/s.

Experiment C-2. (Optional) Effect of Magnetic Field

A large magnetic field is required for significant curvature of either alphas or betas.

Experiment C-3. (Optional) Observing Gamma Rays

Place a drop of the liquid barium in a planchet, and dip the small end of a stopper in it. Shake the excess liquid from the stopper, and insert the stopper into the side of the cloud chamber.

VI ANSWERS TO QUESTIONS

1. The bottom is darkened to provide a dark background against which to see the tracks, which appear to be

white.

2. The windshield fogs up because the air inside the car comes into contact with the cool glass surface. The air is damp because the human body gives off water vapor (from one's breath and also from perspiration). Four people contribute more moisture to the air than one, thus bringing the air inside closer to saturation.
3. Fog forms on a window pane as you blow on it because of the moisture in the air you exhale. The cooler window pane cools this air to the saturation temperature and below.
4. Saying that frost is frozen dew would imply that dew first forms and then freezes. This is not the case. The vapor goes directly to the solid form.
5. If the air is still, the air close to the wet cloth becomes saturated (or nearly so) and evaporation slows down or stops. If the air is moving, saturation does not take place and evaporation continues more rapidly.
6. At body temperature, alcohol evaporates more rapidly than water. The heat (required for this evaporation) comes from the skin. Hence the skin is cooled.
7. The water does not suddenly boil away because heat is required to change the water from liquid to gas forms. This heat must be supplied by the stove and it is supplied continuously over a period of time.
8. During physical exertion more heat is developed in the body and this must be lost by evaporation of perspiration. One then perspires more in order to lose the additional heat.
9. The exhaust gases of jet engines include a large amount of water vapor. By expansion and to a lesser extent by contact with the cooler air, the exhaust gases are cooled below the saturation point for the vapor. "Foreign bodies" in the air and also in the exhaust gas become condensation sites. Incidentally, the exhaust of an automobile is "steamy" for a short time on a cold morning for the same reason. Condensation takes place while the gases are still in the muffler and exhaust pipes. After the muffler and exhaust pipes heat, condensation does not take place enough to be visible in the exhaust.
10. The water had been supercooled because there were few condensation sites. Opening it to the air permitted ice crystals or dust to fall into the water, triggering solidification. It is analogous to the sodium acetate experiment.
11. The blemish can become a bubble site, behaving like foreign matter.
12. Alpha tracks are shorter beyond the paper barrier because they are moving more slowly after they emerge from the paper. They have lost most of their kinetic energy as they moved through the paper.
13. The particle with larger charge exerts a larger force on electrons in the atoms of the vapor. Ionization is caused by this force on an electron in the atom, and hence the larger charge produces more ions. Heavier tracks are caused by more ionizations; i.e., the larger number of ionized atoms provide more condensation sites.
14. A wet source or barrier "kills" alpha tracks, because the thin layer of alcohol stops the alpha particles.
15. Heavier tracks mean more ions were produced along the way. Every time an ion pair is formed, the particle slows down (loses energy). An alpha particle thus loses energy (speed) faster than a beta particle and hence cannot penetrate as much material as a beta particle.
16. By using the formula $\pi(d/2)^2$ for the area of the hole, we assumed that it is a <u>plane</u> circle. The very first equation assumes that the area of the hole is part of the surface of a sphere, which is not a plane. The error is very small provided the diameter of the hole is small

compared with the radius of the sphere (R).

VII POST-TESTS

Test 1

1. A supercooled vapor is one which: (a) has been cooled rapidly; (b) is extremely cold; (c) will solidify if there are condensation sites; (d) is cooled below the temperature of saturation.
2. Charged particle tracks can be seen in a cloud chamber because: (a) alcohol vapor condenses on ions along the path of the particle; (b) ion pairs recombine, giving off radiation; (c) the charged particles are brought to rest in the transparent gas; (d) alcohol is especially volatile.
3. The function of dry ice in the operation of the cloud chamber is to: (a) cool the vapor below the saturation point; (b) remove the heat released as vapor condenses; (c) eliminate "foreign" matter from the gas; (d) provide carbon dioxide vapor for the chamber.
4. Which of the following is not characteristic of ordinary fog? (a) Each droplet forms around a condensation site. (b) It forms only if the air is saturated with water vapor. (c) It is an illustration of the fact that most air molecules are ionized. (d) It is similar to a cloud.
5. Alpha particle tracks in a cloud chamber: (a) are irregularly curved; (b) are irregularly spaced in time; (c) have completely random lengths; (d) are visible only while the alpha particle is moving through the chamber.
6. In using a cloud chamber: (a) it is important to have the chamber evacuated; (b) it is necessary to use a strong radioactive source; (c) a dark background makes the tracks more clearly visible; (d) tracks can be seen anywhere in the chamber.
7. Sodium acetate in liquid form returns to the solid state: (a) when it is cooled; (b) when an alpha particle passes through it; (c) and thereby becomes very cool; (d) when a granule of sodium acetate is added.
8. Dew is formed: (a) when humid air becomes superheated near a surface; (b) when saturated air is further cooled at a surface; (c) when fog falls on to a surface; (d) because the surface is charged.
9. Which of the following processes is common to the operation of a cloud chamber and "cloud seeding" to produce artificial rain? (a) Condensation of supercooled vapor; (b) cooling by expansion; (c) charged particle tracks; (d) absorption of heat energy.
10. Beta tracks in a cloud chamber: (a) are easy to see; (b) are more curved than alpha tracks; (c) can often be seen without a source; (d) are heavier than alpha tracks.
11. Alpha particles, in comparison with beta particles: (a) move faster; (b) have greater penetrating power; (c) have larger charge; (d) have smaller mass.

Test 2

1. A supersaturated vapor: (a) will become a liquid if there are condensation sites; (b) is a gas containing a lot of water vapor; (c) is extremely cold; (d) will rapidly expand, producing droplets.
2. Charged particle tracks can be seen in a cloud chamber because: (a) excited atoms of a gas give off light; (b) ions become condensation sites; (c) the particle moves very slowly because of the low temperature; (d) alcohol is evaporated as the particle passes through it.
3. The function of dry ice in the operation of the cloud chamber is to: (a) keep the alcohol from evaporating too rapidly; (b) lower the temperature so that molecules "stay put" long enough to be seen; (c) stop the alpha particles; (d) supersaturate the alcohol vapor.

4. Clouds and ordinary fog are: (a) results of rapid cooling; (b) supersaturated vapors; (c) caused by ionized air; (d) composed of droplets formed around condensation sites.
5. Which of the following statements about alpha particle tracks is not true? (a) They are (nearly) straight. (b) They end abruptly. (c) They occur at precisely predictable times. (d) They are visible for a few seconds.
6. Which of the following processes is not involved in alpha track formation in a cloud chamber? (a) Supercooling of a liquid; (b) condensation of a vapor; (c) ionization of molecules; (d) loss of kinetic energy of the alpha particle.
7. Sodium acetate in the liquid form: (a) results from heating granular sodium acetate with a few drops of water; (b) absorbs heat as it solidifies; (c) is superheated at room temperature; (d) condenses by cooling.
8. Dew formation does not involve: (a) supersaturation; (b) supercooling; (c) superheating; (d) condensation.
9. Which of the following processes is common to the operation of a cloud chamber and bubble formation in a heated liquid? (a) Supercooling; (b) condensation; (c) superheating; (d) an ion triggers a rapid change of form.
10. Beta tracks in a cloud chamber: (a) are thinner than alpha tracks; (b) cannot be seen beyond thin metal barriers; (c) are straight and heavy; (d) cause supercooling.
11. Beta particles, in comparison with alpha particles: (a) move more slowly; (b) have larger charge; (c) have larger mass; (d) have greater penetrating power.

Test 3

1. Cooling a vapor below the temperature of saturation: (a) will always cause condensation; (b) will cause condensation if it is done rapidly; (c) always causes supersaturation; (d) sometimes causes supersaturation.
2. Charged particle tracks are visible in a cloud chamber because: (a) of the heat given off by condensation; (b) dust particles become condensation sites; (c) ions can trigger condensation; (d) the vapor is superheated.
3. Dry ice is important in the operation of a cloud chamber because: (a) it is very cold; (b) it is a good source of condensation sites; (c) it evaporates instead of melting; (d) it cools the alpha and beta particles so they will stop.
4. Ordinary fog: (a) occurs at the "saturation temperature" of the air; (b) is caused by alpha and beta particles in the air; (c) is caused by supersaturation; (d) is caused by superheating.
5. Alpha tracks in a cloud chamber: (a) occur at regular, predictable times; (b) are the result of ionization; (c) cause supercooling; (d) are extremely difficult to see.
6. In order for alpha tracks to form in a cloud chamber: (a) the chamber must be ionized; (b) the alcohol vapor must have all condensed beforehand; (c) supersaturation must have occurred; (d) the alpha particle must not lose energy.
7. In the experiment with sodium acetate: (a) a superheated solid became a liquid; (b) a superheated liquid became a gas; (c) a supercooled gas became a liquid; (d) a supercooled liquid became a solid.
8. When frost forms on a surface, you can be sure that: (a) a weather report of air temperature of 40°F is incorrect; (b) air became saturated; (c) the surface was charged; (d) evaporation cooled the surface below the freezing point.
9. You studied the following processes: supercooling, supersaturation, condensation, and ionization. Which of the following involves all these processes? (a) Cloud seeding; (b) bubble formation in a heated liquid; (c) dew formation;

(d) track formation in a cloud chamber.

10. Beta tracks in a cloud chamber: (a) are more nearly straight than alpha tracks; (b) are formed by condensation; (c) do not involve ionization; (d) are heavy.
11. Alpha particles, in comparison with beta particles: (a) cause more ions because they move faster; (b) cause fewer ions because they are larger; (c) cause heavier tracks because they have more charge; (d) cause curved tracks because they are smaller.

ANSWERS TO POST-TESTS

Test 1

1. (d)	2. (a)	3. (a)	4. (c)
5. (b)	6. (c)	7. (d)	8. (b)
9. (a)	10. (b)	11. (c)	

Test 2

1. (a)	2. (b)	3. (d)	4. (d)
5. (c)	6. (a)	7. (a)	8. (c)
9. (d)	10. (a)	11. (d)	

Test 3

1. (c)	2. (c)	3. (a)	4. (a)
5. (b)	6. (c)	7. (d)	8. (b)
9. (d)	10. (b)	11. (c)	

VIII LIST OF APPARATUS

Experiment A-1. Operating a Cloud Chamber
Cloud chamber (plastic container)
Stoppers
Radium-226 source (in long test tube)
Mercury thermometer (-10° to +110°C)
Slab of dry ice (~5"x5"x1")
Heavy gloves
Denatured alcohol

Experiment A-2. Dew Formation
Flask (1,000 ml) with stopper
Hot water

Experiment A-3. Solidification of Sodium Acetate
Flask (250 ml) with stopper
Sodium acetate in granular form
Water
Source of heat (Bunsen or alcohol burner, or hot plate)

Experiment B-1. A Closer Look at Cloud Chamber Tracks
Same as for A-1 plus the following:
Onion skin paper (or tissue paper)
Thin aluminum foil
Tweezers

Experiment B-2. Specific Ionization and Scattering
Same as for B-1 plus the following:
Polonium-210 source
Thallium-204 source
Test tubes for sources

Experiment B-3. Radiation Absorption
Same as for B-2 plus the following:
Pieces of index card
Tissue paper
Aluminum foil

Experiment B-4. Measurement of Source Activity
Same as for B-3 except:
Barrier (with hole in center)
Polonium-210 source

Experiment C-1. (Optional) Measurement of Alpha Energies
Cloud chamber
Stoppers
Dry ice
Heavy gloves
Alcohol
"Stick probe"
Unknown alpha source
Linear graph paper

Experiment C-2. (Optional) Effect of Magnetic Field
Same as C-1 plus the following:
Various permanent magnets
Enough wire to make a coil around the cloud chamber
10-A DC power supply
Or a laboratory electromagnet

Experiment C-3. (Optional) Observing Gamma Rays

Same as for C-1 plus the following:
Stopper
Ba-137 in liquid form

IX BIBLIOGRAPHY

Single concept film "Cloud Chamber," produced by Education Communications Center, SUNY at Albany (excellent movie of α and β tracks).

The Amateur Scientist, C. L. Stong, Simon and Schuster, 1960, pp. 305-344 (includes details on making simple cloud chambers).

POT Module On Geiger Counter, Section B (atomic structure, isotopes, radioactivity).

CONTENTS

I INTRODUCTION

This module is about rotational motion. The title device is an electric fan, but essentially any rotating device whose rotational speed can be varied from about 0-2000 rpm (for example, a simple motor) will work. The fan was selected because it has a protective grill in case something flies off.

Section A is primarily about rotational kinematics. The student learns about the terms which describe rotation (rotation angle; rotational speed and rotational acceleration) and how to use several devices for measuring these properties (a turns counter, a stroboscope, a vibrating reed tachometer, and a tach generator). Relations between the rotational terms which describe the motion of an object and the linear terms which describe the motion of a point on it are then developed.

Section B is devoted to rotational dynamics. The student learns about torque and how it produces rotational acceleration. He then uses the tach generator calibrated in Section A to measure the change in rotational acceleration due to changes in the moment of inertia of the rotating object. The rotating point mass is then introduced to explain the observed behavior, and to develop expressions for the moment of inertia and rotational kinetic energy of various objects with simple shapes.

In Section C the ideas of Section A and B are brought together to explain rotational balance, both static and dynamic. The student observes the effects produced by imbalances of both types and learns methods for achieving balance in each case. The causes of the observed effects and the reasons why the balancing techniques work are then discussed using the ideas of center of mass and centripetal and reaction force.

II SPECIAL PREREQUISITES

There are no special prerequisites for this module, except that for the Physics of Technology Series as a whole: high school algebra.

III TABLE OF CONTENTS OF THE MODULE

Acceleration
Summary
Questions And Problems

SECTION B: Explaining Rotational Motion

What Determines Rotational Acceleration
Experiment B-1. Measuring Torque
Experiment B-2. Torque And Rotational Acceleration
Experiment B-3. Rotational Characteristics Of Rigid Objects
The Equation Of Motion
Moment Of Inertia
Rotational Kinetic Energy
Flywheels
A Note About Units
Summary
Questions And Problems

SECTION C: Rotational Balance

What Is Rotational Balance?
The Effects Of Imbalance
Experiment C-1. Observing The Effects Of Static Imbalance
Experiment C-2. Statically Balancing The Disk
Experiment C-3. Observing The Effects Of Dynamic Imbalance
Experiment C-4. Dynamically Balancing A Disk
Forces From Rotation
Center Of Mass
Static Imbalance
Dynamic Imbalance
Balancing Techniques
Summary
Questions And Problems

IV GOALS

The objectives of the <u>Electric Fan</u> module have been included at the begining of the module.

V DISCUSSION OF ACTIVITIES

The module is divided into three Sections, each representing approximately one week's study. It assumes that approximately three class hours and two lab hours will be devoted to each section. A recommended scheduling of class and lab activities, and content of class periods, is as follows:

<u>First Class Period</u>
This should orient the student to the topics that will be covered in the section and to the experiments that will be performed. It should include background material, for example a short film about the topic, and a discussion of the lab experiments and apparatus that will be used.

<u>Laboratory Session</u>
The laboratory experiments should be done before the week's final two class sessions. They generally can be done in a two-hour lab period though slower working students may take somewhat longer.

<u>Second Class Period</u>
This should discuss the laboratory activities and the data taken. The students should be helped in graphing and analyzing their results and in understanding the behavior in terms of the underlying physical laws or principles. If the optional experiments were not done by the students they can be done here as demonstrations. Problems and questions can be assigned at this time.

<u>Third Class Period</u>
This should continue the discussion of the physics underlying the device behavior. The assigned Questions and

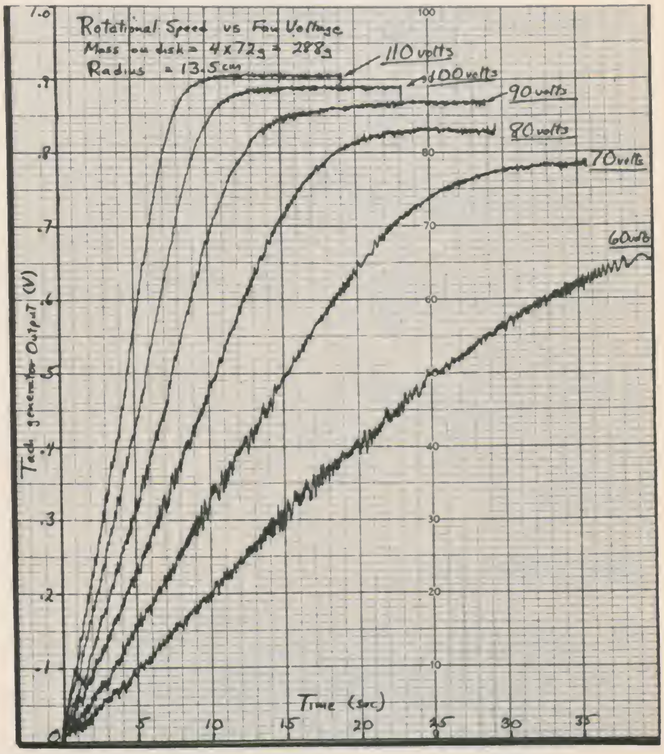
Problems can also be discussed. It is often a good idea to end this class with a short 20-minute quiz on the section's work.

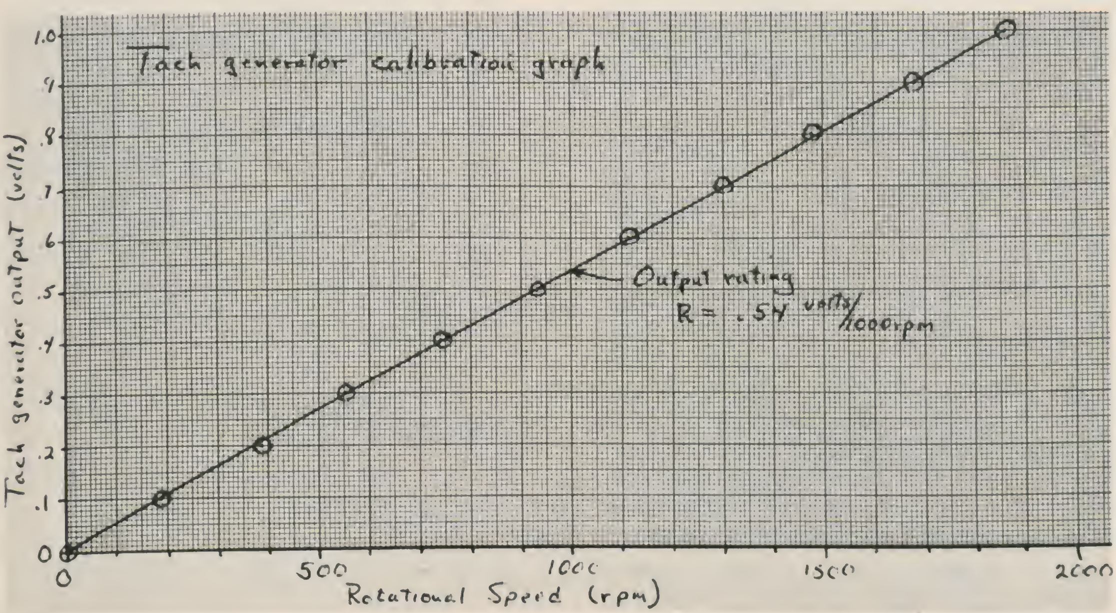
In those experiments in which the disk is accelerating (A-5, B-2, and B-3), the data can be much more easily taken on a servo type strip chart recorder. If one is available it is highly recommended that the student use it. The graphs are drawn immediately and the students can see the changing rotational speed as it happens. Much more data can be taken in a considerably shorter length of time. It is extremely important, however, that the student calibrate the recorder accurately so that he knows the units on each axis.

VI SAMPLE DATA

SECTION A

The data below was taken on a servo recorder. It can be reploted as rotational speed vs rpm using the calibration graph opposite.





Rotational Acceleration Calculations

$$@110V\ \alpha = \frac{.8V}{7s} = \frac{1000rev/min}{.54V} \times \frac{1min}{60s}$$

$$= 3.53 \frac{rev}{s^2} \times \frac{2\pi rad}{rev}$$

$$= 22.2 \frac{rad}{s^2}$$

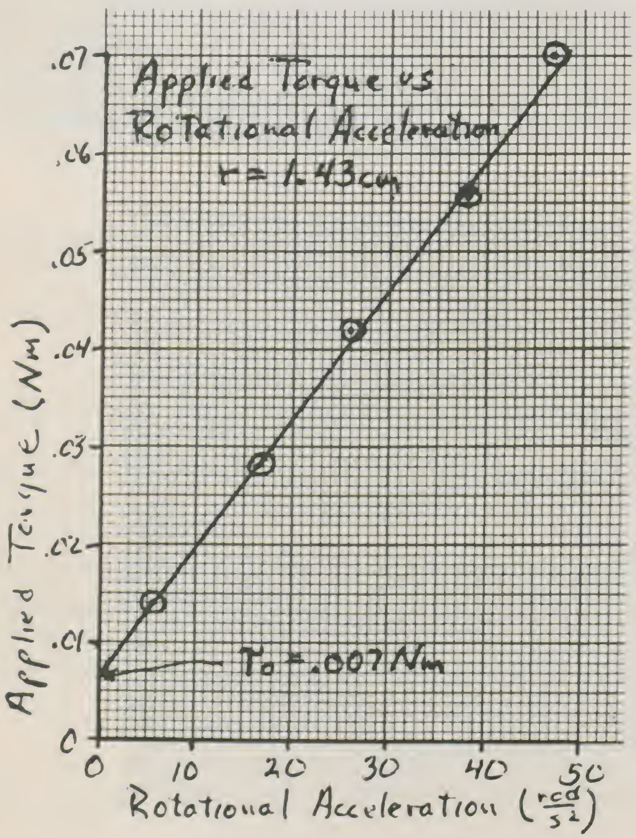
$$@100V\ \alpha = 17.2 \frac{rad}{s^2}$$

$$@\ 90V\ \alpha = 13.2 \frac{rad}{s^2}$$

$$@\ 80V\ \alpha = 9.3 \frac{rad}{s^2}$$

SECTION B

Experiment B-2



Experiment B-3

$$\underline{I}_o = \frac{(\tau - \tau_0)}{\alpha}$$

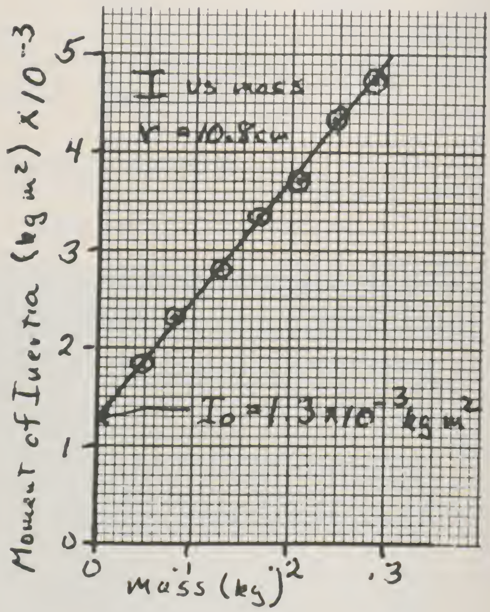
$$= \frac{(.07 - .007)Nm}{48\ rad/s^2}$$

$$= 1.3 \times 10^{-3}\ kg\cdot m^2$$

$$\tau = \underline{I}_o \alpha$$

$$= 1.3 \times 10^{-3}\ kg\cdot m^2 \times 50.4 \frac{rad}{s^2}$$

$$= .066\ Nm$$



$$\text{Slope} = \frac{(5.0-1/3) \times 10^{-3}\ kg\cdot m^2}{.3\ kg}$$

$$= .0123\ m^2$$

$$r = \sqrt{.0123\ m^2}$$

$$= 11\ cm$$

SECTION C - No Data.

VII SOLUTIONS TO QUESTIONS AND PROBLEMS

SECTION A

Questions

1. $\underline{n} \times 100$ rpm
   where $\underline{n} = 0, 1, 2, 3, 4, \ldots$
2. Increase the strobe rate and see if any higher rates also stop the motion. If not, then you are at the true rate.
3. $\Theta = \frac{\underline{d}}{\underline{r}} = \frac{3.4 \text{ ft}}{1.7 \text{ ft}} = 2 \text{ rad} = 114.7°$
4. $\underline{d} = \underline{r}\Theta = \frac{3}{4} \text{ in} \times 1° \times \frac{1 \text{ rad}}{57.3°}$

   $= .013 \text{ in}$
5. Less than one mile.

Problems

1. $\underline{s} = \underline{r}\omega$

   $= \frac{9}{12} \text{ ft} \times 4000 \frac{\text{rev}}{\text{min}} \times \frac{2\pi \text{ rad}}{\text{rev}}$

   $= 18{,}800 \frac{\text{ft}}{\text{min}} \times \frac{1 \text{ min}}{60 \text{ s}}$

   $= 314 \frac{\text{ft}}{\text{s}} \times \frac{1 \text{ mi/h}}{1.46 \text{ ft/s}}$

   $= 215 \frac{\text{mi}}{\text{h}}$

2. $\omega = \frac{1 \text{ rev}}{.03 \text{ s}} = 33.3 \frac{\text{rev}}{\text{s}}$

   $\underline{s} = \underline{r}\omega$

   $= 3 \text{ ft} \times 33.3 \frac{\text{rev}}{\text{s}} \times 2\pi \frac{\text{rad}}{\text{rev}}$

   $= 628 \frac{\text{ft}}{\text{s}}$

3. $\omega = \frac{\underline{s}}{\underline{r}}$

   $= \frac{150 \text{ mi/h}}{1.5 \text{ ft}} \times \frac{88 \text{ ft/s}}{\text{mi/h}}$

   $= 8{,}800 \frac{\text{rad}}{\text{s}}$

4. $\omega = \frac{\underline{s}}{\underline{r}}$

   $= \frac{4000 \text{ ft/min}}{.25 \text{ ft}} \times \frac{1 \text{ min}}{60 \text{ s}}$

   $= 267 \frac{\text{rad}}{\text{s}} \times \frac{1 \text{ rev}}{2\pi \text{ rad}} \times \frac{60 \text{ s}}{\text{min}}$

   $= 2{,}550 \text{ rpm}$

5. $\underline{s} = \underline{r}\omega$

   $= 6 \text{ in} \times 78 \frac{\text{rev}}{\text{min}} \times \frac{2\pi \text{ rad}}{\text{rev}}$

   $= 2{,}900 \frac{\text{in}}{\text{min}}$

   $\underline{s} = \underline{r}\omega$

   $= 3 \text{ in} \times 78 \frac{\text{rev}}{\text{min}} \times \frac{2\pi \text{ rad}}{\text{rev}}$

   $= 1{,}500 \frac{\text{in}}{\text{min}}$

6. $\alpha_{ins} = \frac{\Delta\omega}{\Delta\underline{t}}$

   $= \frac{37.0 - 0 \text{ rev/s}}{0-15.0 \text{ s}}$

   $= -2.47 \frac{\text{rev}}{\text{s}}$

   $\alpha_{avg} = \frac{\Delta\omega}{\Delta\underline{t}}$

   $= \frac{25.0 - 1.4 \text{ rev/s}}{5-25 \text{ s}}$

   $= -1.18 \frac{\text{rev}}{\text{s}^2}$

SECTION B

Questions

1. The wheels should have a minimum kinetic energy.

   $\underline{KE}$ = sum of $\frac{1}{2} \underline{I}\omega^2$ for all the point masses on the wheel.

   $= \frac{1}{2}$ sum of $\underline{mr}^2 \left(\frac{\underline{v}^2}{\underline{r}^2}\right)$

   $= \frac{1}{2}$ sum of $\underline{mv}^2$

Therefore to minimize the $\underline{KE}$ one should minimize the mass of the wheel, $\underline{M}$.

2. You must do an amount of work equal to the kinetic energy of the moving car. This work ultimately appears as frictional heat in the brakes (assuming no engine braking).

3.

4. So that they have a high moment of inertia and thus carry a large rotational kinetic energy. Therefore they act as flywheels maintaining a constant rotational speed.

Problems

1. a) $$\tau = 100\ \text{oz}\cdot\text{in} \times 5.21 \times 10^{-3}\ \frac{\text{lb}\cdot\text{ft}}{\text{oz}\cdot\text{in}}$$

$$= .521\ \text{lb}\cdot\text{ft}$$

b) $$\underline{F} = \frac{\tau}{\underline{r}}$$

$$= \frac{100\ \text{oz}\cdot\text{in}}{\text{in}}$$

$$= 100\ \text{oz}$$

2. $$950\ \text{g}\cdot\text{cm} \times 980\ \frac{\text{cm}}{\text{s}^2} = 9.3 \times 10^5\ \text{dyn}\cdot\text{cm}$$

3. $$\underline{I} = \underline{Mr}^2$$

$$= 9\ \text{kg} \times (.15\ \text{m})^2$$

$$= .20\ \text{kg}\cdot\text{m}^2$$

4. a) $$I_1 = \frac{1}{12}\underline{M\ell}^2$$

$$= \frac{1}{12} \times 18\ \text{kg} \times (12\ \text{ft} \times .305\ \frac{\text{m}}{\text{ft}})^2$$

$$= 20\ \text{kg}\cdot\text{m}^2$$

b) $$\underline{I}_2 = \underline{Mr}^2$$

$$= 45\ \text{kg}\ (6\ \text{ft} \times .305\ \frac{\text{m}}{\text{ft}})^2$$

$$= 134\ \text{kg}\cdot\text{m}^2$$

c) $$\underline{I} = \underline{I}_1 + \underline{I}_2$$

$$= 20 + 134\ \text{kg}\cdot\text{m}^2$$

$$= 154\ \text{kg}\cdot\text{m}^2$$

d) Move toward the center of rotation.

5. $$\alpha = \frac{\Delta\omega}{\Delta\underline{t}}$$

$$= \frac{1{,}800\ \text{rev/min}}{40\ \text{s}} \times \frac{1\ \text{min}}{60\ \text{s}} \times \frac{2\pi\ \text{rad}}{\text{rev}}$$

$$= 4.71\ \frac{\text{rad}}{\text{s}^2}$$

$$\underline{I} = \frac{\tau}{\alpha}$$

$$= \frac{15\ \text{Nm}}{4.71\ \text{rad/s}^2}$$

$$= 3.18\ \text{kg}\cdot\text{m}^2$$

$$\underline{KE} = \frac{1}{2}\underline{I}\omega^2$$

$$= \frac{1}{2}\ 3.18\ \text{kg}\cdot\text{m}^2 \times (1800\ \frac{\text{rev}}{\text{min}} \times \frac{1\ \text{min}}{60\ \text{s}} \times \frac{2\pi\ \text{rad}}{\text{rev}})^2$$

$$= 5.63 \times 10^4\ \text{J}$$

6. $$\underline{I} = \frac{1}{2}\underline{Mr}^2$$

$$= \frac{1}{2} \times 500\ \text{g} \times 7.5\ \text{cm}^2$$

$$= 1.41 \times 10^4\ \text{g}\cdot\text{cm}^2$$

$$\alpha = \frac{\tau}{\underline{I}}$$

$$= \frac{1.3 \times 10^6\ \text{dyn}\cdot\text{cm}}{1.4 \times 10^4\ \text{g}\cdot\text{cm}^2}$$

$$= 93\ \frac{\text{rad}}{\text{s}^2}$$

$$\Delta\underline{t} = \frac{\Delta\omega}{\alpha}$$

$$= \frac{1{,}725 \text{ rev/min}}{93 \text{ rad/s}^2} \times \frac{2\pi \text{ rad}}{\text{rev}} \times \frac{1 \text{ min}}{60 \text{ s}}$$

$$= 1.9 \text{ s}$$

7. Frictional work = $\underline{KE}$
   = Force x Distance
   = $\underline{F} \times \underline{r}\Theta$
   = $\tau\Theta$

Therefore: $\Theta = \frac{\underline{KE}}{\tau}$

$$= \frac{1{,}500 \text{ J}}{75 \text{ Nm}}$$

$$= 200 \text{ rad} \times \frac{1 \text{ rev}}{2\pi \text{ rad}}$$

$$= 31.8 \text{ rev}$$

SECTION C

<u>Questions</u>

1. Drill holes in the heavy side until it is balanced.
2. When acted on by a force the object acts as if all of its mass is concentrated at the center of mass.
3. $\underline{F}_{\underline{R}} = \underline{Mr}\omega^2$, doubling ω increases $\underline{F}_{\underline{R}}$ by 4.
4. Yes, if the rotation axis is not perpendicular to the plane of the disk.
5. In a V-8 the cylinders can be closer together than in a straight eight. Thus the crankshaft is shorter, which reduces the possibility of dynamic imbalance.

<u>Problems</u>

1. $\underline{r} = \frac{\underline{MR}}{\underline{m}}$

$$= \frac{10 \text{ kg}}{.1 \text{ kg}} \times 1 \text{ cm}$$

$$= 100\text{cm}$$

2. $\underline{r} = \frac{\underline{MR}}{\underline{m}}$

$$= \frac{2 \text{ kg}}{.2 \text{ kg}} \times 10 \text{ cm}$$

$$= 100 \text{ cm}$$

3. $\underline{F}_{\underline{R}} = \underline{Mr}\omega^2$

$$= 5\text{kg} \times .01 \text{ m} \times (3000\frac{\text{rev}}{\text{min}} \times \frac{2\pi \text{ rad}}{\text{rev}} \times \frac{1 \text{ min}}{60 \text{ s}})^2$$

$$= 4{,}900 \text{ N}$$

4. $\omega^2 = \frac{\underline{F}_{\underline{R}}}{\underline{Mr}}$

$$= \frac{100 \text{ N}}{10 \text{ kg} \times 10^{-3} \text{m}}$$

$$= 10^4 \frac{\text{rad}^2}{\text{s}^2}$$

$$\omega = 100 \frac{\text{rad}}{\text{s}}$$

5. $\tau_{\underline{w}} = 2\underline{mr}\omega^2\underline{d}$

$$= 2 \times 100 \text{ g} \times 30 \text{ cm} \times (300\frac{\text{rad}}{\text{s}})^2 \times 2 \text{ cm}$$

$$= 1.08 \times 10^9 \text{ dyne·cm}$$

$$= 108 \text{ Nm}$$

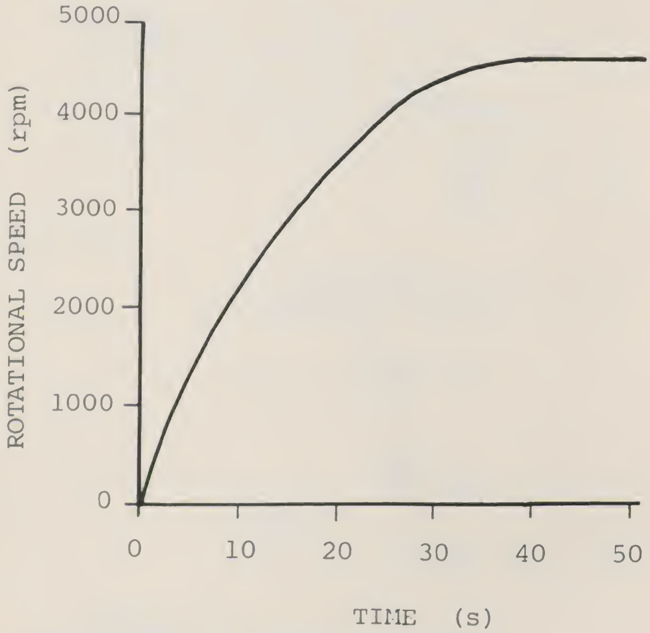
VIII POST-TESTS

<u>Test I</u>

1. Describe how to use a stroboscope to measure rotational speed.
2. An automobile tachometer registers an engine speed of 5000 rpm; what is its rotational speed in radians per second?
3. A digital counter attached to a lathe registers 1000 turns in 15 seconds; what is the rotational speed?
4. If a bicycle with 26 in. diameter

wheels is traveling at 20 mi/h, what is the rotational speed of the wheels in rad/s? (1 mi/h = 1.46 ft/s.)

5. Calculate the instantaneous rotational acceleration at 25.0 s from the graph below.



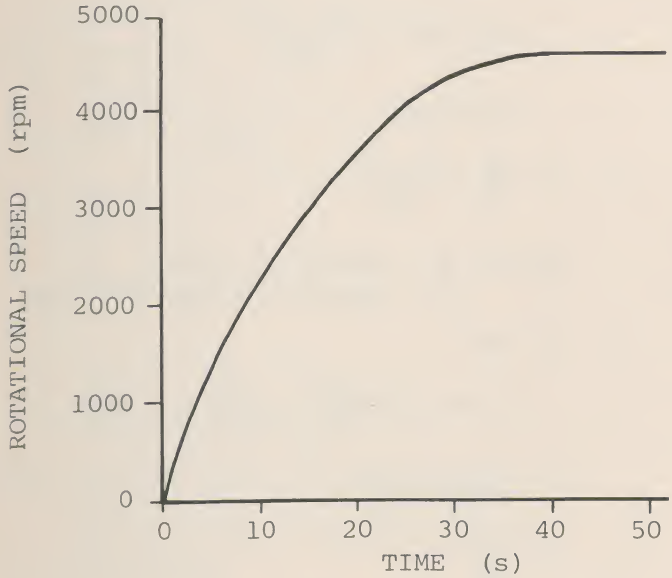
6. Describe how to measure the maximum torque developed in a bicycle wheel by a given rider.
7. What is the moment of inertia of a 100-g ball rotating on the end of a 40-cm string?
8. Which of the following are proper torque units:
   a) $g \cdot cm^2$
   b) oz·in
   c) $dyn \cdot cm^2$
   d) Nm
   e) Nm^2
9. A motor is able to accelerate a flywheel with a moment of inertia of 5 $kg \cdot m^2$ up to a rotational speed of 40 rad/s in 20 s. How much torque does it deliver?
10. Why are flywheels usually shaped like a ring?
11. What is the difference between static and dynamic balance?
12. A centrifuge is rated to withstand a reaction force on its bearings of 1.0 N at a rotational speed of 200 rad/s. How massive a sample can be placed in a test tube at a radius of 10 cm?
13. Describe a way of increasing the size of the mass that can be rotated while staying within the centrifuge ratings of question 12.
14. Describe 3 things you might do to reduce the vibrations in a rotating device that you cannot balance.

Test II

1. Suppose you have stopped a rotating object that looks like the figure below with a strobe at its rotational speed. If you double the strobe rate sketch a picture of what you would expect to see.

2. A photograph turntable is set at 45 rpm; what angle does it rotate through in one minute in degrees? ....In radians?
3. Put your hand flat on the table and raise your index finger, trying to keep it as straight as possible. Calculate the maximum angle (in degrees) through which your finger can move by measuring the length of your finger and the height of the tip above the table.

4. How fast is a bicycle with 26 in. diameter wheels going, when the wheels are rotating at 300 rpm?
5. Calculate the average rotational acceleration from the graph below.



6. What is the difference between starting torque and dynamic torque for a motor?
7. Which of the following is a unit for moment of inertia:
   a) Nm^2
   b) Nm
   c) $kg \cdot m^2$
   d) $kg \cdot m$
8. The armature of a motor which can deliver a torque τ has a moment of inertia I_o. Write an expression for the rate at which it will accelerate an object of moment of inertia I.
9. A motor capable of delivering a torque of 15 Nm accelerates an object to a speed of 60 rad/s in half a minute. What is the moment of inertia of the object?
10. Two ring-shaped flywheels (1 and 2) weigh exactly the same but 1 has twice the moment of inertia of 2. Does 1 have a larger or smaller diameter than 2? By how much?
11. Why is it important to distribute the clothes in a rotating-type washing machine evenly?
12. The center of mass of a lawn mower blade of mass 2 kg is displaced from the center of the axle by .2 cm. What is the reaction force on the bearings at a rotational speed of 30 rad/s?
13. Describe a simple way to balance the lawn mower in question 12.
14. Describe 3 things you might do to reduce the vibrations in a rotating device that you cannot balance?

<u>Solutions To Post-Tests</u>

<u>Test I</u>

1.

2. $\omega = 5000 \frac{rev}{min} \times 2\pi \frac{rad}{rev} \times \frac{1\ min}{60\ s}$

$= 520 \frac{rad}{s}$

3. $\omega = \frac{\theta}{t}$

$= \frac{1000\ rev}{15\ s} \times \frac{60\ s}{min}$

$= 4000$ rpm

4. $\omega = \frac{s}{r}$

$= \frac{20\ mi/h}{13\ in} \times \frac{1.46\ ft/s}{mi/h} \times 12 \frac{in}{ft}$

$= 27 \frac{rad}{s}$

5. $\alpha = \frac{\Delta\omega}{\Delta t}$

$= \frac{(5000 - 2100)\ rev/min}{(39 - 0)s \times 1min/60\ s}$

$= 4{,}461 \frac{rev}{min^2}$

6. Raise the bicycle off the ground and then hang weights on the rim at a maximum radius while the rider stands on a pedal which is horizontal to the ground. The

torque developed is: $\tau = \underline{mgr}$ where $\underline{m}$ is the mass that just counteracts the rider, $\underline{g}$ is the acceleration of gravity and $\underline{r}$ is the wheel radius.

7. $\underline{I} = \underline{mr}^2$

$= 100 \text{ g } (40 \text{ cm})^2$

$= 1.6 \times 10^5 \text{ g}\cdot\text{cm}^2$

8. $\underline{b}$) oz·in
$\underline{d}$) Nm

9. $\alpha = \dfrac{\omega}{\underline{t}}$

$= \dfrac{40 \text{ rad/s}}{20 \text{ s}}$

$= 2 \dfrac{\text{rad}}{\text{s}^2}$

$\tau = \underline{I}\alpha$

$= 5 \text{ kg}\cdot\text{m}^2 \times 2 \dfrac{\text{rad}}{\text{s}^2}$

$= 10 \text{ Nm}$

10. This shape maximizes the moment of inertia, and therefore the kinetic energy, for a given mass.
11. Static balance means that when an object is stationary it has no tendency to turn. Dynamic balance means that when an object is turning it has no tendency to wobble.

12. $\underline{m} = \dfrac{\underline{F}_R}{\underline{r}\omega^2}$

$= \dfrac{1.0 \text{ N}}{.1 \text{ m } (2000 \text{ rad/s})^2}$

$= 2.5 \times 10^{-6} \text{ kg}$

13. Add an equal mass in a test tube on the opposite side. Then the two masses must be equal to within 2.5×10^{-6} kg.
14. See page 55.

Test II

1.

2. $\Theta = \omega\underline{t}$

$= 45 \dfrac{\text{rev}}{\text{min}} \times 1 \text{ min} \times \dfrac{360°}{\text{rev}}$

$= 16{,}200° \times \dfrac{2\pi \text{ rad}}{360°}$

$= 283 \text{ rad}$

3. $\Theta = \dfrac{\underline{d}}{\underline{r}} \times \dfrac{57.3°}{\text{rad}}$

where: $\underline{d}$ = height of finger
$\underline{r}$ = length of finger to joint

4. $\underline{s} = \underline{r}\omega$

$= 13 \text{ in} \times 300 \dfrac{\text{rev}}{\text{min}} \times \dfrac{1 \text{ ft}}{12 \text{ in}} \times 2\pi \dfrac{\text{rad}}{\text{rev}}$

$= 2{,}042 \dfrac{\text{ft}}{\text{min}}$

5. $\alpha = \dfrac{\Delta\omega}{\Delta\underline{t}}$

$= \dfrac{(4{,}500 - 0) \text{ rev/min}}{(40 - 0)\text{s} \times 1 \text{ min}/\ 60 \text{ s}}$

$= 6{,}750 \dfrac{\text{rev}}{\text{min}^2}$

6. Starting torque is the torque developed by the motor when it is starting from rest. It is equal to the torque which must be applied to just stop the motor from turning. Dynamic torque is the torque delivered to an object when it is turning.
7. $\underline{c}$) kg·m^2
8. $\alpha = \dfrac{\tau}{(\underline{I}_o + \underline{I})}$

9. $\alpha = \dfrac{\omega}{\underline{t}}$

$= \dfrac{60 \text{ rad/s}}{30 \text{ s}}$

$= 2 \dfrac{\text{rad}}{\text{s}^2}$

$$\underline{I} = \frac{\tau}{\alpha}$$

$$= \frac{15 \text{ Nm}}{2 \text{ rad/s}^2}$$

$$= 7.5 \text{ kg}\cdot\text{m}^2$$

10. $\underline{I}_1 = 2\underline{I}_2$

$$\underline{Mr}_1{}^2 = 2\underline{Mr}_2{}^2$$

$$\frac{\underline{r}_1}{\underline{r}_2} = \sqrt{2}$$

$$= 1.4$$

$$\underline{d}_1 = 1.4\ \underline{d}_2$$

11. To statically balance it so that when it spins, the reaction forces on the bearings will be minimized.

12. $\underline{F}_{\underline{R}} = \underline{Mr}\omega^2$

$$= 2 \text{ kg} \times .002 \text{ m} \times (30 \frac{\text{rad}}{\text{s}})^2$$

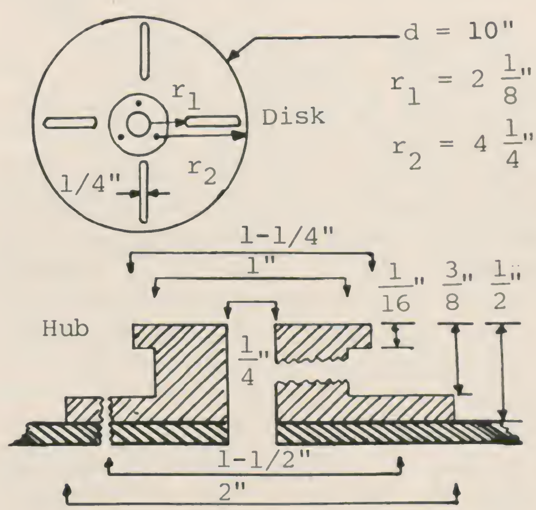
$$= 3.6 \text{ N}$$

13. Place it on a static balancer and file off the end of the side which hangs low until the blade is level.
14. See page 55.

IX LIST OF APPARATUS

SECTION A

Electric Fan, 14" box type with removable grill and blade. It is essential that the fan have a motor that produces a constant torque for various loads and for AC supply voltages down to about 80 V. For example, see the data shown earlier. Some cheaper grade fans do not have these characteristics, so the fan should be tested.
DC electric motor designed to operate at about 1 to 1 1/2 V.
DC voltmeter, 0-1 volt full scale.
Rubber coupling, e.g. 3/16" ID x 3/8" OD rubber tubing
Variable AC power supply, 0-120 V.
Stroboscope, variable 200-2000 fpm and calibrated.
Stopwatch.
Revolution Counter, 3 digit (1-999).
Vibrating Reed, 12" x .375" x .020" strip of spring steel.
Steel Washers (24), 1-1/4" OD x 1/4" ID with m≈10g.
Metal bolts and wing nuts (4), 1/4" x 20.
Aluminium disk with hub, 16 gauge (see drawing below).



SECTION B

Same as Section A.

SECTION C

Same as Section A plus:
Static Balancer, like those used for lawn mower blades but of higher quality if possible.
Spirit Level.
Solder, #18.

INSTRUCTOR'S MANUAL FOR THE FLUORESCENT LAMP

CONTENTS

I INTRODUCTION

The Fluorescent Lamp module is a study of the fluorescent lamp, the light given off by such a lamp, and how this light is related to the energy levels of mercury atoms.

The module is designed to require three full weeks of study for the average student. The laboratory exercises are mostly concerned with the simple observation, and subsequent measurement, of the spectra of various sources of light, particularly those which involve gases. A well-darkened room is necessary for many of the laboratory experiments.

The physics in the module is primarily that of simple waves as applied to light and of the structure of matter. The latter phrase primarily refers to the energy levels of atoms and to the relationship between the structure of atoms and the absorption and emission of light. The process of fluorescence is briefly discussed and phosphors are described.

II SPECIAL PREREQUISITES

Before beginning this module, the students should be familiar with the following physics concepts and procedures:

1. Kinetic energy and how to find it. ($\frac{1}{2}\,\underline{mv^2}$).
2. How to find changes in gravitational potential energy (Wh).
3. Conservation of energy.
4. How to find the work done when a force moves an object in a straight line (Fd).
5. The relationship between work and energy.
6. Electric current.
7. Electrical potential difference (voltage).
8. The attraction and repulsion of electric charges.
9. Potential energy of an electric charge in an electric field.

III TABLE OF CONTENTS OF THE MODULE

Experiment B-3. Analysis of the Mercury Spectrum
A Look Ahead

SECTION C

What Happens to the Coating of the Fluorescent Lamp
Experiment C-1. A Closer Look at the Fluorescent Lamp Spectrum
How Atoms Acquire Energy
A Brief Study of Absorption Spectra
Experiment C-2. The Absorption Spectrum of Sodium
Fluorescence
Experiment C-3. Phosphors and Black Lights
Spectra of Phosphors
Experiment C-4. Band Spectra
Practical Fluorescent Lamps
Experiment C-5. The Fluorescent Lamp
Experiment C-6. Optional

IV GOALS

The objectives of the Fluorescent Lamp module have been included at the beginning of the module.

V. DISCUSSION OF ACTIVITIES

The module is divided into three parts, each representing one week's study.

SECTION A

The first section is primarily a study of light as a wave. The students observe spectra and measure wavelengths. The quantum aspect of light is not mentioned.

There are five experiments in this section. Experiments A-1, A-2, and A-3 may be done as classroom demonstrations if the lab is not available. Experiment A-4 is designed as a take-home exercise, and Experiment A-5 is optional.

The teacher may want to use some of the following activities during this first week.

First Class Period

1. With a ripple tank, demonstrate wave motion.
2. With a 35-mm projector and colored slides, demonstrate the additive and subtractive nature of color.

Experiment A-1. A First Look at Lamps and Spectra

The purposes of this experiment are to introduce the student to spectra and to methods of recording them, and to allow convenient comparison of various spectra.

Second Class Period

1. Discuss the results and questions of Experiment A-1.
2. Introduce Experiment A-2.

Experiment A-2. The Spectrum of a Flame

In this experiment, students who know that rock salt is sodium chloride may wonder why the light from the flame is assumed to be only from sodium atoms. In the flame, sodium chloride dissociates into sodium atoms and chlorine atoms. These atoms acquire kinetic energy from the heat of the flame and can be excited by collisions with other atoms. The sodium atoms have one electron in an otherwise empty outer shell (valence +1). This electron is easily excited from its ground state to higher energy levels by collisions with other atoms. But chlorine, which is missing one electron in an otherwise filled outer shell, cannot be excited from its ground state by collisions with other atoms in the flame. Thus, no chlorine spectrum is seen in the flame.

Experiment A-3. Measurement of Wavelength

This experiment allows the student to measure wavelength. A slit is used to help students see why a slit is essential to the grating spectrometer.

Experiment A-4. Take-Home Experiment

It is interesting to ask your students to "pool" their take-home observations. Can they classify the lights they see as incandescent, fluorescent, and other?

Experiment A-5. (Optional) The Diffraction Grating

This is a quantitative experiment on diffraction. It may be done as a classroom demonstration.

Third Class Period

1. Discuss the $\lambda \underline{f} = \underline{v}$ relationship, using the analogy of a train: to measure the speed of a train you could count the number of cars which pass you in one minute (frequency) and multiply that by the average length of a car (wavelength).
2. You might elaborate on the nature of the electromagnetic spectrum. You could stress that radio waves are really long and that x-rays are really short. You might also discuss the possible source of various frequencies. For example, gamma radiation has a nuclear origin, while the origin of x-rays is atomic. It is interesting to note the rather general (although not absolute) rule that as the size of the radiating system increased, the radiated wavelength increases.
3. Administer post-test A.

SECTION B

The second section of the module stresses the relationship of spectra to atomic structure. Both quantitative and qualitative methods are used. There are three experiments, one of which may be done as a classroom demonstration if lab time is limited.

The teacher may wish to supplement the discussion with additional atomic theory.

First Class Period

1. Show the film "Powers of Ten," an excellent introduction to the relative sizes of atoms and nuclei.
2. In discussing energy levels for an atom, you could elaborate on the analogy with the ledges on a hillside (Figure 18). If the students know how to compute changes in gravitational potential energy, they could compute energies of "transitions" for a stone falling down the hillside.

Experiment B-1. Spectra of Other Gases

In this experiment, the spectra of various gases (mercury, hydrogen, neon, helium, nitrogen, oxygen) are measured quantitatively. The gas in the fluorescent lamp should be readily identified as mercury. Students have already measured the wavelengths of these lines.

Please warn your students of the shock hazard with the discharge tube power supply. It supplies about 5,000 volts, with very little current.

Second Class Period

1. Discuss the results of Experiment B-1.
2. Discuss energy transitions and light. Stress the point that line intensity does not depend on the energy of the transition, but rather on the number of atoms that undergo that particular transition. This is, in turn, related to the probability that an atom will undergo that particular transition. So measurements of relative brightness of spectral lines leads to knowledge about the relative probabilities of different transitions.
3. Consider what spectra tell us about energy levels. Use Figure 21, a simplified energy level diagram for mercury.

Experiment B-2. The Spectrum of Hydrogen

In this experiment, the student

quantitatively measures various values of hydrogen.

Experiment B-3. Analysis of the Mercury Spectrum

This experiment illustrates the relationship between wavelength and displacement of images. This relationship is not really linear. But for first order spectra, the angle is sufficiently small that the relationship is valid.

Third Class Period

1. Discuss the results of the experiments.
2. Administer post-test B.

SECTION C

This section is more directly related to the operation of fluorescent lamps. Fluorescence and its importance in the operation of fluorescent lamps is emphasized.

There are four experiments, one or two of which may be done as classroom demonstrations if the lab is not available. During this third week, the teacher might use some of the following activities.

First Class Period

1. Introduce Experiment C-1.
2. Discuss the design of the fluorescent lamp.
3. Show film loop "Absorption Spectra."

Experiment C-1. A Closer Look at the Fluorescent Lamp.

In this experiment, the student probes deeper into the principles behind the fluorescent lamp.

Experiment C-2. The Absorption Spectrum of Sodium

In this experiment, the students study the concept of absorption spectra. Some students may have difficulty in seeing the absorption line. It appears as a very thin black line in the yellow portion of the sodium spectrum. Since it is, in effect, an image of the incandescent source, it will have the same shape as the filament of the lamp. You will probably need a very dark room.

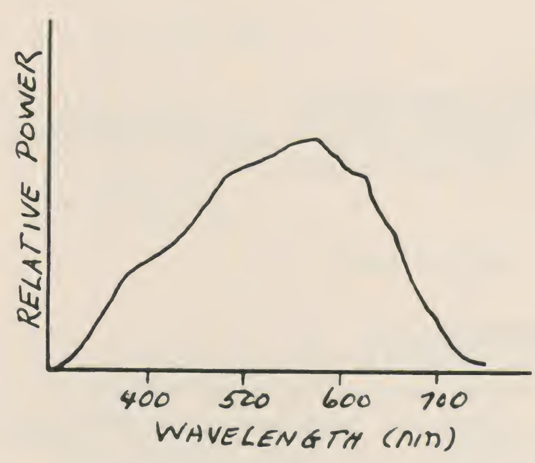
Second Class Period

1. Discuss results of Experiments C-1 and C-2.
2. Demonstrate phosphors and black lights. Coat some gadget with fluorescent powder. After many students have had an opportunity to handle the object, turn off the room lights and turn on a black light. Everyone who has touched the object will glow.

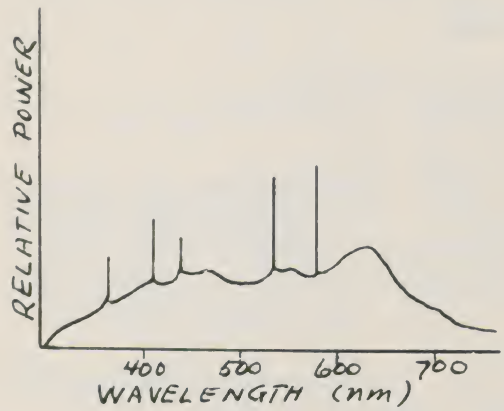
Experiment C-3. Phosphors and Black Light

In this experiment, the student learns about fluorescence. The chalk will be "excited" by both the fluorescent lamp and the incandescent lamp. Both light sources emit some ultraviolet light, which causes the chalk to fluoresce. The chalk under the fluorescent lamp will fluoresce more strongly than that under the incandescent lamp because of the greater ultraviolet output of the fluorescent lamp.

The spectrum of a typical phosphor:

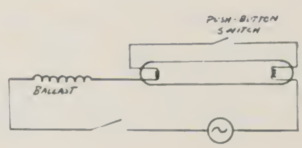


The spectrum of a typical fluorescent lamp. The "spikes" represent the line spectrum of the mercury vapor in the lamp.



Experiment C-4. The Fluorescent Lamp.

This experiment studies the fluorescent lamp in detail. The circuit of the fluorescent lamp is shown below.



Third Class Period

1. Discuss results of experiments.
2. Administer post-test C.

VI. SAMPLE DATA

Experiment A-1

1. A carefully made crayon record, with correct spacing between lines, of each spectrum observed allows convenient comparisons of various spectra.

Experiment A-3

1.

	Left Side	Right Side
First image	0.15 m	0.16 m

	Average of both sides	L
First image	0.155 m	0.5 m

	Left Side	Right Side
Second image	0.48 m	0.50 m

	Average of both sides	L
Second image	0.49 m	0.5 m

$\lambda = \underline{dx}/\underline{n} \quad \sqrt{\underline{L}^2+\underline{x}^2}$

for $\underline{n} = 1$, $\lambda = (1900 \text{ nm})(0.155 \text{ m}) / (1)(\sqrt{0.5^2 + 0.155^2} \text{ m}^2)$

≈ 560 m

2. Typical student measurements of wavelength for the fluorescent lamp spectrum are:

Yellow line	573 nm	(578.0 nm, accepted value)
Green line	532 nm	(546.1 nm, accepted value)
Blue line	435 nm	(435.8 nm, accepted value)
Violet line	405 nm	(404.7 nm, accepted value)

Experiment A-5

n	x(left)	x(right)	x(mean)
1	0.15 m	0.16 m	0.155 m
2	0.48 m	0.50 m	0.49 m
3	1.1 m	1.3 m	1.2 m

The value of L used for these measurements was L = 0.5 m. So we have

$$\text{Tan } \theta = \frac{X}{L}$$

and for n = 1, $\tan \theta = \frac{0.155}{0.5} = .310$

$$\simeq \sin \theta \simeq .310$$

More acurately,

$$\sin \theta = \frac{X}{\sqrt{L^2 + X^2}} = 0.296$$

But $\sin \theta = \frac{n\lambda}{d}$

Since $\lambda \simeq 590$ nm, and n = 1,

$$d = \frac{590 \text{ nm}}{0.31} = 1.90 \times 10^{-6} \text{ m}$$

For $d = 1.90 \times 10^{-6}$ m, the calculated number of lines per mm is 1/d = 526 lines per mm. This is 13,360 lines/inch. The actual grating used had 13,400 lines/inch.

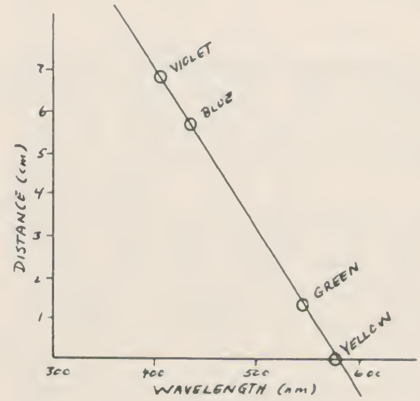
Experiment B-2

Typical student data for the hydrogen spectrum are:

Red line	650 nm	(656.3 nm, accepted value)
Blue-green line	485 nm	(486.1 nm, accepted value)
Blue line	430 nm	(434.0 nm, accepted value)
Violet line	410 nm	(410.1 nm, accepted value)

Experiment B-3

1. Calibration curve



2. Typical measured values are:

λ = 573 nm yellow
= 532 nm green
= 500 nm blue-green
= 435 nm blue
= 405 nm violet
= 365 nm ultraviolet

The frequency of a particular wave is calculated from

$$f = \frac{3 \times 10^8 \text{ m/s}}{\lambda}$$

while the energy may be computed either from E = hf or from

$$E = \frac{1240 \text{ eV}}{\lambda \text{ (in nm)}}$$

λ	f	E
573 nm	5.2×10^{14} Hz	2.16 eV
532 nm	5.6×10^{14} Hz	2.33 eV
500 nm	6.0×10^{14} Hz	2.48 eV
435 nm	6.9×10^{14} Hz	2.85 eV
405 nm	7.4×10^{14} Hz	3.06 eV
365 nm	8.2×10^{14} Hz	3.40 eV

VII ANSWERS TO QUESTIONS

The module's problems and questions should be discussed in class when possible.

1. The cellophane appears blue because it allows only blue light to pass through it. If you wrap an incandescent lamp with blue cellophane, only the blue light passes through; but since the cellophance is not a perfect blue filter, it allows a fairly broad range of colors identifiable as blue to pass. So what you would actually see through a diffraction grating is a blue "smear" of light. It is just the continuous spectrum less the yellow-red portion.
2. Blue light is always nearest the source. Then come green, yellow, orange, and finally red, which is farthest from the source.
3. The spectrum is a <u>line spectrum</u>, since it apparently contains light of a single color. More careful analysis of the sodium spectrum confirms this by showing many additional lines.
4. The continuous spectrum consists of an infinite number of closely spaced frequencies (colors), each of which creates its own image when the light passes through a diffraction grating. The continuous spectrum you see consists of an infinite number of images of the source, each of which is displaced slightly relative to its neighbors and each of which is a slightly different color. These overlapping images cause the spectrum to appear as a "smear" of colors.
5. As pointed out in the answer to Question 4, the spectrum actually consists of a series of overlapping images of the source. In order to measure accurately the wavelengths of light from a source such as sodium flame, this overlapping of images must be eliminated. This is done by reducing the size of the source. The slit provides well-defined and easily located images of the yellow light in the flame. It also reduces the effects of the turbulence of the flame.
6. Since moonlight is reflected sunlight, its spectrum should be continuous, as is sunlight.
7. The grating with fewer grooves.
8. The grating with the smaller spacing between lines (the larger number of lines per mm) spreads the images out more.
9. There are usually one or two spectral lines that can be identified with the color of the discharge lamp. For example, mercury light appears to be blue, and the spectrum shows both a blue and a violet line. But the mercury spectrum also contains other colors (yellow and green) which are not apparent from the color of the lamp itself.
10. The slip is not needed to view the spectrum of the discharge tube because the tube itself is narrow enough to allow good separation of the various colored images.
11. The mercury discharge tube and various street lamps will have the same spectrum as the clear end of the fluorescent lamp. Most mercury street lamps also have a phosphor coating, but the mercury lines are clearly evident.
12. The ratio of the diameter of the atom to the diameter of its nucleus is

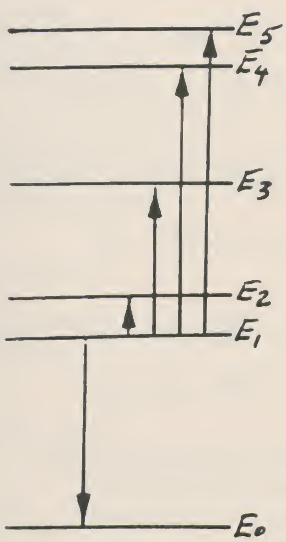
$$\frac{1.5 \times 10^{-8} \text{ cm}}{6.8 \times 10^{-13} \text{ cm}} = 2.2 \times 10^{4}$$

If the nucleus is to be represented by an orange, diameter = 8 cm, the diameter of the electron cloud would be

$8 \text{ cm} \times 2.2 \times 10^4 = 1.8 \times 10^5 \text{ cm}$

$= 1800 \text{ m} \approx 1 \text{ mile}$

13. Phosphorus. The number of protons determine what element the atom is.
14. To ionize the atoms, the energy of the atom must be increased to the ionizaton energy level. That is, enough energy must be provided to the atom to remove the electron completely from the influence of the nucleus. Thus the energy of the ionized atom free electron system is higher than the energy of the un-ionized atom.
15.



16. No. The ground state is, by definition, the lowest energy state.
17. The fact that you can see four lines in the hydrogen spectrum indicates the existence of at least four different energy levels (perhaps more) for the hydrogen atom. Thus, the single electron must move between several pairs of energy levels to produce the spectrum you see. Each line in the spectrum represents one transition between energy levels.
18. The proton may be regarded as an ionized hydrogen atom. If it "captures" an electron to form a hydrogen atom in the ground state, the electron must undergo a transition between the energy level corresponding to the ionization energy and the ground state energy level. Thus, the atom would emit radiation.
19. As the ions are produced, they move under the influence of the applied voltage. Thus they constitute a current. This process will continue until the current is too large for either the electrodes of the lamp or the external circuit.
20. Some of the ions do recombine, but most are accelerated by the applied voltage to energies which are too high to allow recombination; the ions move too fast to allow recombination.
21. By shining light with a continuous spectrum through exhaust gases, one can view the absorption spectra of the gases. Since an absorption spectrum is a "fingerprint" just as an emission spectrum is, the gases can be identified by comparison of their spectra with standard spectra. Similarly, heavy elements in the sun have been identified from solar absorption spectra, just as helium was identified.
22. The light that is providing the continuous spectrum for the absorption experiment is shining toward the observer. The atoms which absorb light do re-radiate the light, often at essentially the same frequency as that which was absorbed. But they re-radiate the light in all directions, instead of toward the observer. Thus the intensities of absorbed frequencies appear to be decreased relative to the intensities of other frequencies. This results in the appearance of dark lines.
23. The wavelength of the emission and

absorption spectra you observed for sodium were the same. Sodium atoms absorb a certain frequency of yellow light and emit the same frequency. Fluorescence implies absorption of one frequency and subsequent emission of a lower frequency.

24. Atoms in the luminous dial can absorb light, usually ultraviolet, and can remain in excited states for several minutes. This <u>persistence</u> means that at any time after the exciting light source is turned off, enough atoms are returning to ground state and thereby emitting visible light to cause the dial to be visible. This process continues until all the excited atoms have returned to ground state.
25. Many white or brightly colored objects are treated with phosphors which fluoresce enough in the normal amount of ultraviolet light from sunlight or fluorescent lamps to enhance the "whiteness" or the "brightness." Many detergents what promise to "whiten and brighten" your wash also contain such phosphors.
26. The phosphor is on the inside of the lamp because the ultraviolet light which excites the phosphor cannot penetrate the glass.

SOLUTIONS TO PROBLEMS

1. The wavelength is computed from $\lambda \underline{f} = \underline{c}$, where $\underline{f}$ and $\underline{c}$ are known for each case.

For $\underline{f}$ = 60 Hz, $\lambda = \dfrac{\underline{c}}{\underline{f}} = \dfrac{3 \times 10^8 \text{ m/s}}{60 \text{ Hz}}$

$= 5 \times 10^6$ m

For $\underline{f}$ = 56 kHz, $\lambda = \dfrac{3 \times 10^8 \text{ m/s}}{5.6 \times 10^5 \text{ Hz}}$

= 5400 m

For f = 7×10^{14} Hz,

$$\lambda = \frac{3 \times 10^8 \text{ m/s}}{7 \times 10^{14} \text{ Hz}} = 430 \text{ nm}$$

2. The frequency is computed from $\lambda \underline{f} = \underline{c}$, where λ and $\underline{c}$ are known.

For λ = 400 nm, $\underline{f} = \dfrac{\underline{c}}{\lambda}$

$= \dfrac{3 \times 10^8 \text{ m/s}}{4 \times 10^{-7} \text{ m}} = 7.5 \times 10^{14}$ Hz

For λ = 600 nm, $\underline{f} = \dfrac{3 \times 10^8 \text{ m/s}}{6 \times 10^{-7} \text{ m}}$

$= 5 \times 10^{14}$ Hz

For λ = 90 nm, $\underline{f} = \dfrac{3 \times 10^8 \text{ m/s}}{9 \times 10^{-8} \text{ m}}$

$= 3.3 \times 10^{15}$ Hz

For λ = 1 m, $\underline{f} = \dfrac{3 \times 10^8 \text{ m/s}}{1 \text{ m}}$

$= 3 \times 10^8$ Hz

For λ = 100 m, $\underline{f} = \dfrac{3 \times 10^8 \text{ m/s}}{100 \text{ m}}$

$= 3 \times 10^6$ Hz

3. 120 nm is ultraviolet
500 nm is visible
5000 nm is infrared
430 nm is visible
10 nm is ultraviolet
650 nm is visible
1000 nm is infrared

4. We know that the energy in electron volts is given by

$$\underline{E}(\text{eV}) = \frac{1240 \text{ eV}\cdot\text{nm}}{\lambda \text{ (in nanometers)}}$$

$$\lambda \text{ (in nanometers)} = \frac{1240 \text{ eV}\cdot\text{nm}}{5 \text{ eV}}$$

$= 248$ nm

The frequency is given by

$$\underline{f} = \frac{3 \times 10^8 \text{ m/s}}{248 \times 10^{-9} \text{ m}} = 1.2 \times 10^{15} \text{ Hz}$$

5. The wavelength of the blue-green line is 486 nm.

$$\underline{E}(\text{eV}) = \frac{1240 \text{ eV}\cdot\text{nm}}{\lambda \text{ (in nanometers)}}$$

$$= \frac{1240 \text{ eV}\cdot\text{nm}}{486 \text{ nm}} = 2.55 \text{ eV}$$

6. The only possible downward transitions from the 7.73-eV state are those labeled A, B, and C in Figure 21 and the transition from the 7.73-eV level to the ground state. The wavelengths of transitions A, B, and C are 546 nm, 435 nm, and 405 nm, respectively. The wavelength of the fourth transition is calculated as in Problem 5.

$$\lambda(\text{nm}) = \frac{1240 \text{ eV}\cdot\text{nm}}{7.7 \text{ eV}} = 161 \text{ nm}$$

This transition is not an allowed transition for the emission spectrum of mercury.

7. As in Problem 5.

$$\lambda = \frac{140 \text{ eV}\cdot\text{nm}}{20{,}000 \text{ eV}} = 0.062 \text{ nm}$$

$$= 6.2 \times 10^{-11} \text{ m}$$

This is an x-ray.

VIII POST-TESTS

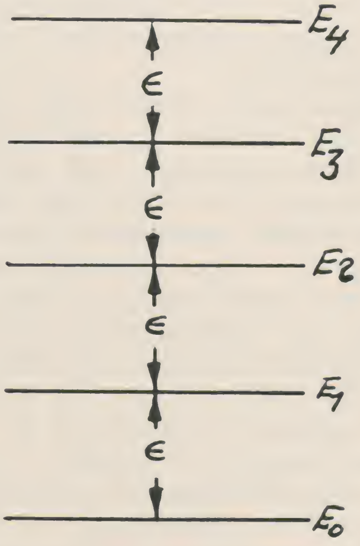
Test A

1. The spectrum produced when light from a mercury discharge tube is viewed through a diffraction grating is: (a) a continuous spectrum; (b) the same as the spectrum of an ordinary fluorescent lamp; (c) a line spectrum; (d) a band spectrum.
2. The wavelength of blue light is: (a) longer than the wavelength of red light; (b) shorter than the wavelength of red light; (c) longer than the wavelength of infrared light; (d) shorter than the wavelength of ultraviolet light.
3. Doubling the frequency of a particular wave: (a) doubles its wavelength; (b) does not affect its wavelength ; (c) halves its wavelength; (d) doubles the speed of the wave.
4. The primary source of light in a fluorescent lamp is: (a) a filament; (b) a vacuum; (c) mercury vapor; (d) argon vapor.

Test B

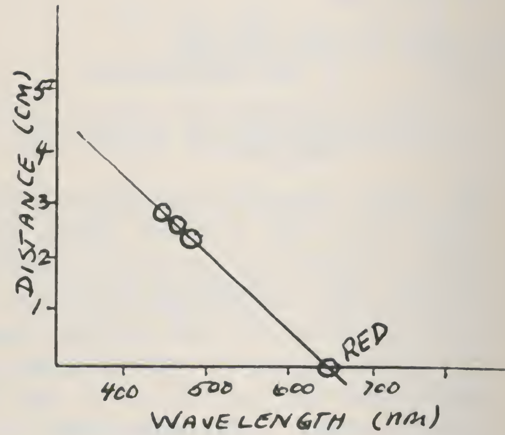
1. The nucleus of a carbon atom is: (a) composed only of protons; (b) about 10^{-4} times as large as the carbon atom; (c) composed of protons, electrons, and neutrons; (d) mainly responsible for the emission of light from carbon atoms.

The following three questions refer to the hypothetical energy level diagram shown, and to the atom it represents.



2. If the atom is initially in state E_0, and it absorbs an amount of energy equal to 3 ε, it will then be in state: (a) E_0; (b) E_1; (c) E_2; (d) E_3; (e) E_4.
3. After absorbing energy 3 ε, the atom can emit light of frequencies proportional to: (a) ε; (b) 2 ε; (c) 3 ε; (d) all the above.

4. The atom in its ground state could never absorb an amount of energy equal to: (a) $\varepsilon/2$; (b) ε; (c) $2\ \varepsilon$; (d) $4\ \varepsilon$.
5. The most important characteristic of mercury related to its use in fluorescent lamps is the fact that: (a) mercury is a liquid at ordinary temperatures; (b) light from a mercury discharge is blue; (c) light from a mercury discharge is strongly ultraviolet; (d) mercury vapor is easily ionized.
6. In a fluorescent lamp, mercury atoms are primarily excited by: (a) collisions with other mercury atoms; (b) collisions with mercury ions and electrons; (c) ultraviolet light emitted by the glow discharge around the cathodes; (d) light produced by the phosphor.
7. When an atom fluoresces, it absorbs light of one frequency and emits light of: (a) the same frequency; (b) higher frequencies; (c) lower frequencies.
8. Measurements of the wavelength of the yellow line in the sodium emission spectrum, and of the "wavelength" of the dark line in the sodium absorption spectrum leads to: (a) knowledge of the ground state energy of the sodium atom; (b) knowledge of the energy difference between two energy levels of the sodium atom; (c) knowledge of the number of electrons in the electron "cloud" of sodium.
9. The sketch below is a calibration curve for a photograph of the hydrogen spectrum, similar to the one you made for mercury. The wavelength of a line which is 4 cm from the red line is: (a) in the infrared portion of the spectrum; (b) in the green portion of the spectrum; (c) about 350 nm.
10. Which of the following is not a form of energy which is important in the operation of a fluorescent lamp?



(a) Electrical energy; (b) kinetic energy of mercury ions; (c) energy of excited mercury atoms; (d) energy of excited atoms in a phosphor; (e) energy of ultraviolet light; (f) kinetic energy of atoms in a phosphor.

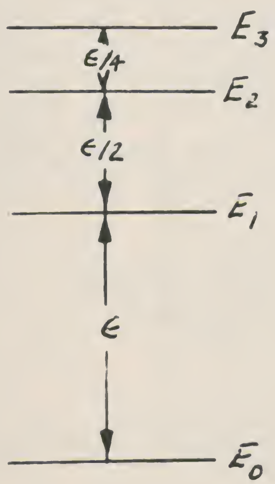
Test C

1. A grating spectrometer consists of: (a) a diffraction grating, a slit, and a light source; (b) a diffraction grating, a slit, and a scale; (c) a diffraction grating, a slit, a scale, and a light source.
2. The frequency of yellow light is: (a) slightly lower than the frequency of green light; (b) slightly lower than the frequency of red light; (c) slightly higher than the frequency of blue light; (d) higher than the frequency of ultraviolet light.
3. The frequency of spectral line "A" is determined to be 5×10^{14} Hz. A second spectral line, "B" has frequency 3×10^{14} Hz. The wavelength of line "A" is: (a) 15 times the wavelength of line "B"; (b) 5/3 the wavelength of line "B"; (c) 3/5 the wavelength of line "B"; (d) 1/5 the wavelength of line "B".
4. The spectrum produced by light from a typical fluorescent lamp:

(a) appears to be continuous; (b) is a line spectrum; (c) consists mostly of ultraviolet light; (d) contains a bright red line.

5. In a bunsen burner flame, the atoms are primarily excited by: (a) collisions with other atoms; (b) light given off by the burning gas; (c) absorption of electromagnetic energy from the flame.
6. Which of the following statements about atoms is not true? (a) An atom is composed of a positively charged nucleus and a negatively charged electron cloud. (b) The particles from which atoms are built are electrons and protons; (c) The nucleus of the atom is much smaller than the atom itself. (d) The number of negative charges in an atom is normally the same as the atomic number of the atom.

The next three questions refer to the hypothetical energy level diagram shown, and to the atom whose structure it represents.



7. The emission spectrum of this atom would probably contain lines whose frequencies are proportional to: (a) ε, $\varepsilon/2$, $\varepsilon/4$; (b) $3\varepsilon/4$, $3\varepsilon/2$, $7\varepsilon/4$; (c) all the above; (d) none of the above.
8. This atom could never absorb an amount of energy equal to: (a) $\varepsilon/2$; (b) ε; (c) $5\varepsilon/4$; (d) $3\varepsilon/2$.
9. The shortest wavelength in the emission spectrum of the atom is: (a) $hc/3\varepsilon$; (b) $4hc/7\varepsilon$; (c) $4hc/3\varepsilon$; (d) $4hc/\varepsilon$. (h is Plank's constant and c is the speed of light.)
10. The fact that you observed four lines in the spectrum of hydrogen is evidence of the existence of: (a) exactly four different energy levels in the hydrogen atom; (b) exactly five different energy levels in the hydrogen atom; (c) at least four different energy levels in the hydrogen atom; (d) three different energy levels in the hydrogen atom.
11. Phosphors are materials which can absorb light of a particular wavelength and then give off light of: (a) the same wavelength; (b) shorter wavelengths; (c) longer wavelengths.
12. The primary function of the ballast in a fluorescent lamp circuit is to: (a) maintain a constant voltage in the circuit; (b) dissipate heat energy; (c) prevent the recombination of ions; (d) prevent the excessive build-up of current.
13. In order to calibrate your photograph of the mercury spectrum, you were required to: (a) plot known wavelength against known frequency for the visible lines of the mercury spectrum; (b) plot frequency against separation of the visible lines of the mercury spectrum; (c) plot measured wavelength against measured distance for the visible lines of the mercury spectrum.
14. The series of boxes which appears on the next page is intended to represent in sequence the various forms into which energy is converted in the operation of the fluorescent lamp. Place into each empty box the letter which identifies the form into which the energy in the box to follow is changed.

(a) Ultraviolet light energy; (b) energy of excited mercury atoms; (c) kinetic energy of atoms in a phosphor; (d) energy of ions; (e) energy of excited atoms in the phosphor.

ANSWERS TO POST-TESTS

Test A

1. (c) 2. (b) 3. (c)
4. (c)

Test B

1. (b) 2. (d) 3. (d)
4. (a) 5. (c) 6. (b)
7. (c) 8. (b) 9. (c)
10. (f)

Test C

1. (b) 2. (a) 3. (c)
4. (a) 5. (a) 6. (b)
7. (c) 8. (c) 9. (b)
10. (c) 11. (c) 12. (d)
13. (c) 14. (d), (b), (a), (e)

IX LIST OF APPARATUS

Experiment A-1

Lamp board
Diffraction grating
Crayons

Experiment A-2

Diffraction grating
Fischer burner or bunsen burner with a wire screen
Rock salt
Crayons

Note

1. Be sure that the burner and/or wire screen are as clean as possible before beginning the experiment so that the student can adjust the burner to get a clear flame before adding the salt.
2. It is important to use rock salt to get a bright yellow flame.
3. WARNING! Salt which falls off the burner may be very hot, even though it doesn't look it. Caution your students about this.

Experiment A-3

Same as for A-2, plus the following:
Meter stick and supports
Cardboard slit
Grating spectrometer

Note

1. The slit is used to help students see why a slit is essential to the grating spectrometer. This slit should be about 1/4" wide by 2½" high. It can be cut out of lightweight cardboard or other suitable opaque material.
2. The number of images your students will be able to see depends on the number of ridges per inch your gratings have. The closer together the lines are, the greater the angular separation of the images. For a grating of 13,000 lines per inch, no more than three images will be visible on each side of the source.

Experiment A-4

Diffraction grating
3 x 5 index card
Masking tape

Experiment A-5

Same as for A-3 plus supports for meter stick.

Experiment B-1

Power supply for discharge tubes
Diffraction grating
Grating spectrometer
Discharge tubes: mercury, hydrogen, neon; helium; nitrogen, oxygen.
Crayons

Experiment B-2
- Discharge tube power supply
- Hydrogen discharge tube
- Grating spectrometer

Experiment B-3
- Discharge tube power supply
- Mercury discharge tubes
- Glass diffraction grating
- Camera

Note
1. The photographic procedure is straightforward. You will need a camera whose exposure you can control.
2. Place a white, or shiny, pointer under the yellow line of the spectrum you want to photograph. This is particularly necessary for a black and white photograph. If you do not have a single lens reflex camera, you will have to locate the pointer by looking through the grating. Be sure that the position of the grating is the same as it will be when taped to the camera.
3. Tape the diffraction grating to the lens of the camera. Be sure that the "lines" on the grating are vertical when you are ready to expose the film.
4. If you use a Polaroid camera with an electric eye, use black and white high-speed film. First, focus the camera on the discharge tube, then rotate the camera slightly until it faces the first order spectrum. The source should not appear in the photograph. With the room dark, depress the shutter button and hold it down until the electric eye closes it. If the photo is overexposed you will need to experiment with shorter exposure times. You can close the shutter whenever you want by releasing the button.
5. If you have a 35-mm camera, you can get good results with either black and white film or color slide film. Remember that you will have to take pictures sufficiently far in advance of the actual laboratory meeting to allow for development. Typical exposures are:
   ASA 125 black and white film, 1 to 5 s at f/28
   ASA 64 color slide film, 1 to 8 s at f/2.8
6. The photograph should show at least two lines that are not visible with either the hand-held diffraction grating or the grating spectrometer. One of these lines is blue-green and the other is ultraviolet.

Experiment C-1
- Lamp board
- Diffraction grating

Experiment C-2
- Same as for A-2 plus "showcase" lamp

Experiment C-3
- Lamp board
- Diffraction grating
- Discharge tube power supply
- Discharge tubes: iodine; carbon dioxide
- Black light
- Fluorescent minerals
- Fluorescent chalk
- Fluorescent powder paints
- Various colored liquids in test tubes for absorption experiments

Note
1. There are many possibilities for solutions which will provide good absorption band spectra. You may wish to experiment with various solutions of potassium permanganate, aqueous ammonium dichromate, copper sulfate, methyl red indicator (acidic or basic), chlorophyll, hemoglobin.
2. The iodine and carbon dioxide spectra will show emission bands.

Experiment C-4
- Lamp board:

OPTIONAL DEMONSTRATION AIDS

The teacher may find the following aids helpful.

16 mm film

"Powers of Ten," Charles Eames Studios, 901 Washington Blvd., Venice, California 90291.

8 mm film loop

"Absorption Spectra," by Franklin Miller. Available from most audio-visual suppliers.

CONTENTS

I INTRODUCTION

The geiger counter is the basis for discussions of radioactivity and nuclear processes.

Section A includes elementary observations with a geiger counter, an introduction to statistical analysis of data, and an experiment demonstrating counting losses that can be ascribed to the resolving time of the counter.

Section B starts with absorption experiments as a means of identifying the three basic kinds of nuclear radiation (alpha, beta, and gamma). This leads into a discussion of nuclear structure, isotopes, radioactive decay, and detailed characteristics of α, β, and γ radiations. It ends with an optional experiment on the half-life of barium-137.

Section C is concerned with the construction of the geiger counter itself, and how an incoming bit of radiation triggers a voltage pulse. Details of the operation are brought out by experiments on pulse height, determination of the plateau, and a measurement of resolving time.

The module is designed to require three weeks. The subject matter of each section is sufficiently different to make it possible also to terminate the study at the end of Section A or Section B.

Theoretical discussions are closely woven together with laboratory exercises, but all instructions for activities are set off in such a way that the student will have no difficulty identifying them. Several "thought questions" and problems are scattered through the module at appropriate places.

The module is written so that a student should be able to proceed with little lecturing and lends itself nicely to various forms of self-paced learning.

A special word should be said about the "thought questions." They cannot be answered purely on the basis of what is said in the text. They are meant as stimuli for <u>further</u> thought, combining what the students have learned with common sense and what they already know from previous experience. Probably the best way to use the thought questions would be as the basis for class discussions or discussions involving small clusters of students. As such, they can serve very well both as review of material covered in the text and also as stimuli for thinking of the relevance of the various ideas to other situations.

II SPECIAL PREREQUISITES

Before you work through this module, you should understand a few ideas about energy, work, and electric charge. Specifically, you should be familiar with:

1. Kinetic energy ($1/2\ \underline{m}\underline{v}^2$), and how to find it.
2. How to find changes in gravitational potential energy ($\underline{Wh}$).
3. Conservation of energy.
4. How to find the work done when a force moves an object along a

straight line (Fd).

5. The relationship between work and energy.
6. Electric current.
7. Electrical potential difference (voltage).
8. The attraction and repulsion of electric charges.
9. Potential energy of an electric charge in an electric field.
10. The procedure for operating an oscilloscope.

III TABLE OF CONTENTS OF THE MODULE

IV GOALS

The specific goals are listed on page 4 of the module itself. Generally, these goals relate to three interrelated concepts: (1) the elementary interpretation and management of experimental data; (2) the three different types of radioactivity and their properties; and (3) the nature and construction of the geiger counter itself.

V DISCUSSION OF LABORATORY ACTIVITIES

Experiment A-1. An Introduction to Counting

Comments:

1. The instructor will need to determine the proper setting of the power supply voltage by consulting the manufacturers' specifications or by running a plateau curve on each instrument.
2. Instruction booklets on the functions of the various apparatus controls and the procedure for observing counts are usually available from the equipment manufacturer.
3. Since the beta radiation from the carbon-14 source has very low energy (maximum 0.156 MeV), it is easily stopped by the thicker absorbers. A more detailed study of absorption is made in Section B.
4. You might try using a small speaker connected directly to the output terminals of the geiger counter instead of using the radio.

Sample data:

Following is a set of sample data for the experiment on distance dependence and background. Student data should show the general decrease but cannot be expected to follow these values in detail.

Distance in Centimeters	Counts per Minute
1	2563
2	1878
5	355
8	167
12	120
20	84
Background	52

Experiment A-2. Are Counts Repeatable?

Comments:

The teacher should emphasize that few precise statements can be made about repeatability or uncertainty. All counting data are approximate. Nonrepeatability is a basic feature of radioactivity and not the result of any error in the geiger counter.

Sample data and calculations:

For 10 one-minute runs, the following data were obtained:

174	169
177	153
174	180
156	182
177	202

Using only the first run, the estimated uncertainty (spread) is $\sqrt{174}$ or ± 13.2. This means that the counts observed in successive runs should generally fall in the range from 161 to 187. Seven of the 10 readings do fall in this range. (Theoretically, 68% of a large number of runs should yield results in the range between $\underline{n}$ and $\underline{n} \pm \sqrt{\underline{n}}$, where $\underline{n}$ is the overall average.) The fractional uncertainty is 1/13.2, or 7.6%.

For all runs the overall average is $\underline{N}/10$, where $\underline{N}$ is the grand total of the counts observed, or 1744. Then the average counting rate and its uncertainty are:

Average counting rate = 174.4 counts/min

Uncertainty in the average $= \sqrt{\underline{N}}/10$ = 41.8/10 = 4.2 counts/min

Note that the fractional uncertainty of the overall average is 4.18/174.4, or 2.4%, which is considerably less than for the first run. Thus, more data mean less fractional uncertainty.

Experiment A-3. Do Counts "Add Up"?

Comments:

The inital counting rates are not too critical. Any counting rates below 4,000 per minute will suffice. The instructor should check to see that the initial count rate for each source is low enough to avoid overloading.

Sample data: (corrected for background)

Number of Counts per Minute		
Trial	Source 1	Source 2
1	1,851	1,780
2	2,836	2,788
3	5,008	4,791
4	10,526	10,174
5	28,066	27,433

Number of Counts per Minute		
Trial	Total	1 & 2 Together
1	3,631	3,726
2	5,624	5,597
3	9,789	9,774
4	20,700	20,020
5	55,499	52,111

The numbers under "total" are the sums of Source 1 and Source 2 readings, whereas "1 and 2 together" are the readings when the sources are used simultaneously. Note that the results do pretty well "add up" for moderate counting rates, but there are losses for very high counting rates.

Experiment B-1. Radiation Absorption

Comments:

1. It is preferable to find a position for each source so that the counting rate without the absorber is about the same for each source.
2. It is important that a background counting rate be taken and subtracted from each reading with a source.

Sample data:

Source	Counts (No Absorber)	Counts (Index Card)
Cobalt-60	1174 (1150)	991 (967)
Americium-241	1083 (1059)	49 (25)
Thallium-240 3	1168 (1144)	844 (820)

Source	Counts (Foil Absorber)	Counts (Lead Absorber)
Cobalt-60	1003 (979)	849 (825)
Americium-241	51 (27)	21 (0)
Thallium-240 3	796 (772)	35 (9)

Background counting rate was 24 counts/min. The number of counts for each case, corrected for background, is shown in parentheses. Note that the radiation from thallium is absorbed to some extent and that that from cobalt is absorbed very little by any of the absorbers. The radiation from americium is unusual: most of it is absorbed even by the index card and all of it by the lead sheet. A very weak gamma ray accompanies the alpha particle, and penetrates the index card and metal foil.

Experiment B-2. An Optional Measurement of the Half-Life of Barium-137

Comments:

1. One minigenerator should suffice for an entire class of 20 students and should last for several years.
2. Complete instructions for the chemical separation of barium-137 from the parent element, cesium-137, are included with the minigenerator.
3. Disposable rubber gloves should be worn to reduce possible danger from radioactive materials.
4. One drop of the eluate is usually sufficient. It should be placed as near the port as possible. In fact, the geiger counter box can be suspended on end immediately above the planchet, with the port above the liquid eluate.
5. It is important that students keep a record of running time as well as time interval. Thus, a stop watch (or preset timer) and a clock or watch are needed. A wall clock can be used if students work in pairs.
6. Background must be recorded and subtracted from each counting rate. Since a small amount of the cesium-137 comes out with the barium-137, the background will now include counts from this isotope. Take the background counting rate with the planchet in place, at least 30 minutes after the half-life experiment.
7. Planchets should be discarded after use.

Sample data and calculations:

t_1 (s)	t_2 (s)	t	Counts	Corrected Counts
0	15	7.5	2665	2649
30	45	37.5	2310	2294
60	75	67.5	1966	1950
90	105	97.5	1804	1788
120	135	127.5	1543	1527
150	165	157.5	1411	1395
180	195	187.5	1167	1151
210	225	217.5	1050	1034
240	255	247.5	892	876
270	285	277.5	813	797
300	315	307.5	709	693

330	345	337.5	601	585
360	375	367.5	561	545
390	405	397.5	507	491
420	435	427.5	451	435
450	465	457.5	367	351
480	495	487.5	345	329
510	525	517.5	267	251
540	555	547.5	255	239
570	585	577.5	214	198
600	615	607.5	197	181
630	645	637.5	179	163
660	675	667.5	136	120
690	705	697.5	119	103
720	735	727.5	114	98
750	765	757.5	112	96
780	795	787.5	102	86
810	825	817.5	90	74
840	855	847.5	77	61
870	885	877.5	65	49
900	915	907.5	60	44
930	945	937.5	48	32
960	975	967.5	49	33

In the table above are given data and corrections for background, which was found to be 63 counts per minute. In the table, $\underline{t_1}$ and $\underline{t_2}$ refer to running time at the beginning and end, respectively, of a particular interval; $\underline{t}$ is the running time at the center of the interval; number of counts is for 15 seconds in each case. The corrected data are shown in the graph on the next page. Points Aa, Bb, and Cc are pairs representing a decrease in counting rate by a factor of 2. The time for these cases are as follows:

Aa: = 156 s
Bb: = 162 s
Cc: = 159 s

The mean of these three values of the half-life is 159 seconds, compared with the accepted value of 156 seconds.

Experiment C-1. Production of Voltage Pulses

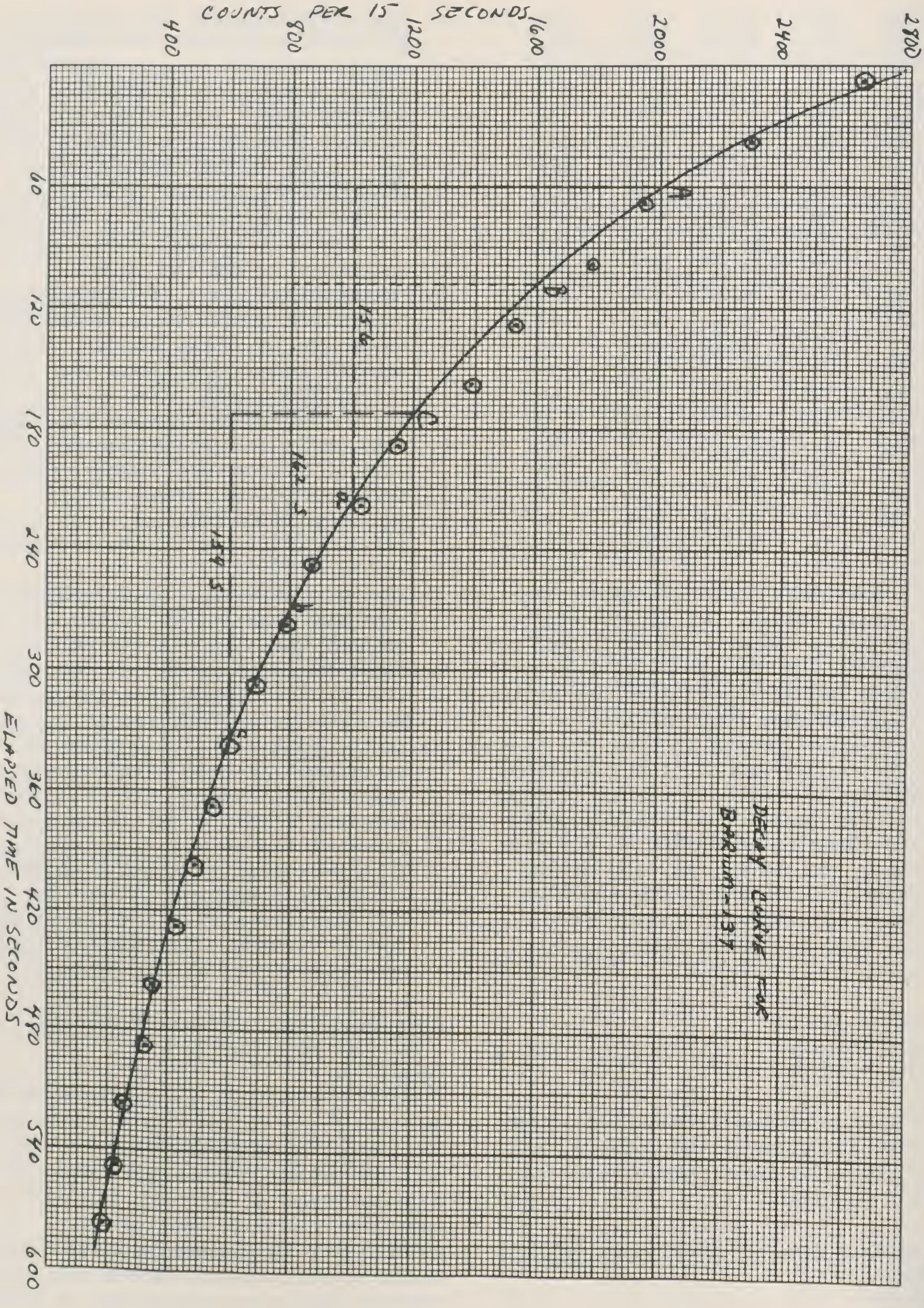
Comments:

1. (Experiment C-1a.) The instructor may need to discuss the schematic circuit diagram symbols and to provide a simple introduction to the oscilloscope. Pulses may not look exactly like the one shown in Figure 14. Often switch contacts make intermittent connection at first. In that case the pulse in interrupted (perhaps several times) as it increases to maximum value.
2. (Experiment C-1a.) At high counting rates some pulses will be observed to be smaller than others. These smaller pulses are those that occur a very short time after another pulse, before the geiger tube has completely recovered from the earlier pulse. If the oscilloscope has a triggered sweep, these smaller pulses will be bunched close to the first pulse shown on the oscilloscope screen.
3. (Experiment C-1b.) It is suggested that the students be warned not to connect the wires to the battery until the instructor has checked the circuit to see that it is wired as shown in the diagram of Figure 18.
4. (Experiment C-1b.) The point of this experiment is that this circuit is exactly similar to that of the geiger counter, with the switch taking the place of the geiger tube. The geiger tube essentially closes a switch to establish a current in the rest of the circuit, giving a pulse at the output terminals similar to the one observed in the simple circuit.

Experiment C-2. Effect of Applied Voltage on Count Rate

Comments:

The counting rate should be zero for values of the voltage up to, perhaps, 300 volts, then quickly rise to the plateau value. This means that over a large range of voltage, the counting rate does not vary considerably. As the voltage is further increased, the counting rate starts increasing. The student should be warned not to continue

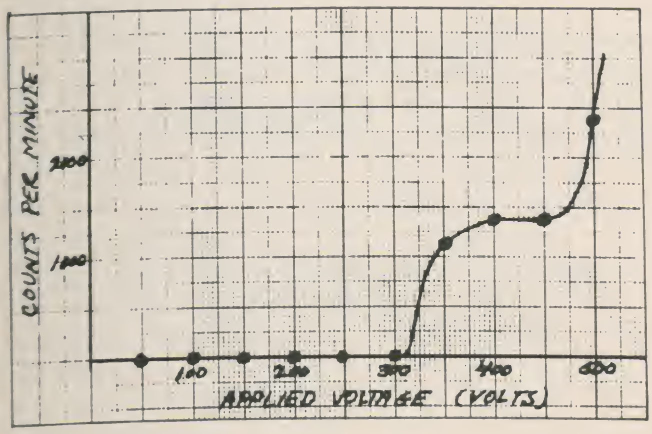

COUNTS PER 15 SECONDS
400
800
1200
1600
2000
2400
2800
60
120
180
240
300
360
420
480
540
600
ELAPSED TIME IN SECONDS
DECAY CURVE FOR
BARIUM-137
A
B
C
156
162.5
159.5

the experiment for voltages much higher than the plateau voltage. Permanent damage to the geiger tube can result.

Sample data:

Applied Voltage	Counts per Minute
0	0
50	0
100	0
150	0
200	0
250	0
300	0
350	1126
400	1395
450	1388
500	2380

These data are plotted on the graph below. Note that the plateau runs from about 400 volts to about 450 volts.



Experiment C-3. Resolving Time

Comments:

1. You may want to show the students how to derive the formula for resolving time in terms of observed counting rates. This can be done by first deriving the formula:

$$R = \frac{R_o}{1 - R_o\tau}$$

relating observed counting rate R_o to true counting rate R (in counts per second). R is the rate at which ionizing radiation enters the geiger tube, potentially causing a count, and actually causing a count if the circuit has recovered from the previous count. Each time a count is registered, the circuit becomes inoperative for a time τ (the resolving time). In one second the circuit is inoperative during the total time $R_o\tau$, since R_o is the rate at which the counts are registered. Then, in one second the time available to incoming particles is not one second but $(1 - R_o\tau)$ seconds. This is sometimes called the real time. The observed counting rate R_o has the same relationship to true counting rate R as $(1 - R_o\tau)$ seconds has to 1 second. Thus,

$$\frac{R_o}{R} = \frac{(1 - R_o\tau)\ \text{sec}}{1\ \text{sec}}$$

or

$$R = \frac{R_o}{1 - R_o\tau}$$

To derive the expression for τ in terms of observed counting rates, let R_1', R_2', and R_{12}' be the true counting rates corresponding to observed counting rates R_1, R_2, and R_{12}, respectively. Then

$$R_1' = \frac{R_1}{1 - R_1\tau} \qquad R_2' = \frac{R_2}{1 - R_2\tau}$$

$$R_{12}' = \frac{R_{12}}{1 - R_{12}\tau}$$

But $R_{12}' = R_1' + R_2'$, since for these quantities, losses are not considered. Thus,

$$\frac{R_{12}}{1 - R_{12}\tau} = \frac{R_1}{1 - R_1\tau} + \frac{R_2}{1 - R_2\tau}$$

This is an equation relating τ and observed counting rates. Cleared of fractions, it can be reduced to the form

$$\underline{R}_1\underline{R}_2\tau\ (2 - \underline{R}_{12}\tau) = \underline{R}_1 + \underline{R}_2 - \underline{R}_{12}$$

This is a quadratic equation in τ, but a good approximation can be obtained by dropping the term $\underline{R}_{12}\tau$ in parentheses. (This is equivalent to assuming that counting losses are small compared with the combined counting rate.) Using this approximation, we have

$$2\underline{R}_1\underline{R}_2\tau = \underline{R}_1 + \underline{R}_2 - \underline{R}_{12}$$

or

$$\tau = \frac{\underline{R}_1 + \underline{R}_2 - \underline{R}_{12}}{2\underline{R}_1\underline{R}_2}$$

in agreement with the formula in the module.

2. Since different geiger tubes and circuits have different resolving times, the data taken in Experiment A-3 should be used as a guide in determining the counting rates to be used for the resolving time experiment. Counting rates from the two sources should be pretty much the same (not different by more than a factor of 2) and large enough to produce some losses but preferably not more than 20% of the total.

Sample data and calculations:

The sample data are given below, with corrected values given in parentheses:

$\underline{R}_1$	=	485.2/s (484.8)
$\underline{R}_2$	=	466.6/s (466.2)
$\underline{R}_{12}$	=	883.8/s (883.4)
Background	=	0.44/s

The resolving time is then

$$\tau = \frac{\underline{R}_1 + \underline{R}_2 - \underline{R}_{12}}{2\underline{R}_1\underline{R}_2}$$

$$\tau = \frac{485.2 + 466.6 - 883.8}{2(485.2)(466.6)}$$

$$= \frac{68.0\ \mathrm{s}}{2(485.2)(466.6)}$$

$$= 1.5 \times 10^{-4}\ \mathrm{s}$$

Using this value of τ, the corrected values ($\underline{R}_1'$, $\underline{R}_2'$, and $\underline{R}_{12}'$) for each of the observed counting rates are

$\underline{R}_1' = 523.4$
$\underline{R}_2' = 501.7$
$\underline{R}_{12}' = 1019.4$

Then the percentage loss can be calculated for each case:

$$\underline{R}_1 : \%\ \text{loss} = \frac{\underline{R}_1' - \underline{R}_1}{\underline{R}_1}$$

$$= \frac{523.4 - 485.2}{523.4}$$

$$= \frac{38.2}{523.4}$$

$$= 7.3\%$$

$\underline{R}_2$: % loss = 7.0%

$\underline{R}_{12}$: % loss = 13.3%

VI OTHER ACTIVITIES

Use of a Survey Meter:

If a survey meter is available, it would be instructive and interesting for your students to do some "prospecting" in the laboratory. A strong source (e.g., the thallium-204

source #1 or #2) can be hidden and the students told to find it using the survey meter.

Sources and Radiation Safety:

The sources used in the module are unlicensed, low-activity sources, but the instructor should exercise care in seeing that students do not misuse them. A short filmstrip Radiation Safety, available from The Nucleus, Inc., Oak Ridge, Tennessee, might be shown to the class if time permits. Sources (as well as rooms or containers where sources are kept) are required to display the International Radiation Symbol.

Film Showing:

The PSSC film Random Events is an excellent treatment of simple ideas of statistics as applied to nuclear phenomena.

Balancing Equations of Nuclear Chemistry:

You may find that charge-mass equations are useful for describing nuclear events. In this approach, charge and mass numbers are indicated by numbers before and after the chemical symbol. For example, a proton is ${}^{1}_{1}H$, an alpha particle is ${}^{4}_{2}He$, and an electron is ${}^{0}_{-1}e$. Equations involving this notation must balance for charge and mass number. For example, the decay of carbon-14 is written

$$ {}^{14}_{6}C \rightarrow {}^{14}_{7}N + {}^{0}_{-1}e $$

Neutrinos:

The discussion of beta decay in the text is incomplete in that neutrinos and antineutrinos are not mentioned.

When a negative beta particle is emitted, an antineutrino is also emitted. When a positive beta particle is emitted, or when an orbital electron is captured, a neutrino is also emitted. In either case the energy of the beta particle is not fixed because the neutrino (or antineutrino) carries away some of the energy lost by the nucleus.

What's Inside the Geiger Counter Box?

You might want the students to open the geiger counter box and examine the actual circuit as they read about it and study the diagram of a typical circuit.

VII ANSWERS TO QUESTIONS

1. A survey meter would be preferable in applications in which one needs to obtain a rapid indication of the rate of radiation entering the detector. It is especially useful in prospecting and radiation monitoring, where compactness and portability are important assets.
2. A source gives out particles in all directions. At a given distance, D, from the source the radiation would be approximately equal through each unit area of a sphere of radius D, centered at the source. As this distance increases, the total area through which radiation passes is greater, so the radiation per unit is less. The counter responds to the radiation entering the window, which has a fixed area. As the distance between the source and the counter increases, this area becomes a smaller fraction of the total area available to the radiation.
3. Normally, counts are due to the source and background combined. That is, the presence of the source does not affect the counts due to background. Thus, to get the effect of the source alone, background must be subtracted. (This is in essence repeated as Question 6, where a more definite answer can be given. Here it should serve to stimulate thinking.)
4. Yes. Different measurements might yield slightly different results,

because of error in reading the ruler and because the length of whatever is being measured might be different at different points of measurement. In fact, many of the ideas applicable to analysis of counting data also apply to analysis of repeated measurements of length.

5. Background radiation can be thought of as radiation from another source. Thus, in effect a geiger counter responds to two sources simultaneously. If counting rates are not very high, the rates add up, or the observed counting rate is the sum of the two counting rates (the source and background). Thus, to obtain the effect of the source, background must be subtracted.
6. Gamma radiation is the most penetrating kind of radiation, and it has no charge or mass. Thus, we could tentatively say that for larger charge and mass, penetrating ability decreases. As will be seen later, the alpha particle has the least penetrating ability for these reasons.
7. The element is oxygen. The atomic number determines the element, and this in turn is the number of protons in the nucleus.
8. Radon-222 has 86 protons and 136 neutrons in its nucleus. Emitting an alpha particle reduces the proton number by 2 and also reduces the neutron number by 2. Thus, the new atom has 84 protons and 134 neutrons in its nucleus. It is polonium-218.
9. A proton changes into a neutron (and a neutrino is emitted). The atomic number decreases by one.
10. Tellurium-131 has 52 protons and 79 neutrons in its nucleus. Negative beta decay changes these numbers to 53 and 78, respectively. This is an atom of iodine-131.
11. Since alpha decay causes the atomic number to be reduced by two, two electrons will eventually leave the electron cloud. (Note the balance, in that eventually the alpha particle adopts two electrons and becomes a neutral helium atom). Gamma radiation does not result in a change in the electron cloud.
12. The probability is the same, since radioactive atoms do not "age."
13. The table shows the same number of electrons as protons. For an ionized atom, the number of electrons is less than the number of protons (usually less by one).
14. The order is: index card, metal foil, lead sheet. This is also the list in the order of increasing amount of material that must be penetrated. Thus, radiation absorption is essentially density dependent.
15. Kinetic energy is $1/2\ \underline{m}\underline{v}^2$. Thus,

$$1/2\ \underline{m}\underline{v}^2 = 1/2\ \underline{M}\underline{V}^2$$

where small letters refer to the beta particle and capital letters refer to the alpha particle. This can be written in the form

$$\frac{\underline{V}^2}{\underline{v}^2} = \frac{\underline{m}}{\underline{M}} = \frac{1}{7300}$$

$$\frac{\underline{V}}{\underline{v}} = \frac{1}{\sqrt{7300}} = \frac{1}{85.4}$$

Thus the beta particle is moving 85.4 times faster than the alpha particle.

16. The pulse height is affected by power supply voltage and also the value of $\underline{R}_L$, though the latter was not shown by experiment.
17. Just before the switch is closed, the voltmeter would read 1.5 volts. Soon after the switch is closed, the reading would go to zero.
18. Since alpha particles have least penetrating ability, the window would have to be thinner than for beta particles.
19. Since heavy (high-density) materials absorb gamma rays more readily than lighter materials,

one would make the window of a heavy metal. Thickness would have to be a compromise between causing no interaction (very thin) and absorbing the gamma ray and stopping the electrons that are knocked out of the metal atoms.

20. They are much larger than electrons and hence move more slowly than the electrons (accelerated toward the central wire). Their slow speed prevents them from ionizing other atoms.

21. For a very high voltage, a continuous conduction could take place. This means that, once started, the rapidly moving electrons keep up the ionization process indefinitely. For moderately high voltages above the plateau, conduction can take place for a much longer time than usual. In any case, permanent damage can result.

SOLUTIONS TO PROBLEMS

1. Fractional uncertainty = $1/\sqrt{N}$. We want to make this less than 2%.

$$\frac{1}{\sqrt{N}} < 0.02$$

$$\sqrt{N} > 50$$

$$N > 2500$$

Thus, at least 2500 counts would have to be taken in order that the uncertainty be less than 2%.

2. For run #1, uncertainty $= \sqrt{10{,}786}$

$$= \pm 103$$

For run #2, uncertainty $= \sqrt{10{,}462}$

$$= \pm 102$$

For run #3, uncertainty $= \sqrt{10{,}577}$

$$= \pm 103$$

3. For all the data, $N = 31{,}825$, $\sqrt{N} = 178$, total time is 30 min.

Average counting rate $= \dfrac{31{,}825 \text{ counts}}{30 \text{ min}}$

$$= 1061 \text{ counts/min.}$$

Uncertainty in counting rate

$$= \frac{178 \text{ counts}}{30 \text{ min}}$$

$$= 5.9 \text{ counts/min.}$$

4. If the half-life is 1.5 hours, 7.5 hours is 5 half-lives. In each half-life the number of atoms is reduced by a factor of 2. Then 1/32 of the atoms will still be in the sample.

5. $V = IR$

$$I = \frac{V}{R} = \frac{10 \text{ V}}{5 \times 10^6 \,\Omega} = 2 \times 10^{-6} \text{ A}$$

6. $R_o = 30{,}000/\text{min}$
$= 500/\text{s}$

$$R = \frac{R_o}{1 - R_o\tau} = \frac{500/\text{s}}{1 - (500)(4 \times 10^{-4})}$$

$$= \frac{500}{1 - 0.2} = \frac{500}{0.8} = 625$$

$$\%\text{ loss} = \frac{R - R_o}{R} \times 100\%$$

$$= \frac{625 - 500}{625} \times 100\%$$

$$= \frac{125}{625} \times 100\%$$

$$= 20\%$$

7. We know that $(R - R_o)/R = 0.08$ and $R_o = 30{,}000/\text{min} = 500/\text{s}$.

$$\frac{R - 500}{R} = 0.08$$

$\underline{R} = 543$

Also, $$\underline{R} = \frac{\underline{R_o}}{1 - \underline{R_o}\tau}$$

$$543 = \frac{500}{1 - 500\tau}$$

$$543 - (500)(543)\tau = 500$$

$$\tau = \frac{43}{(500)(543)}$$

$$= 1.58 \times 10^{-4} \text{ sec}$$

VIII POST-TESTS

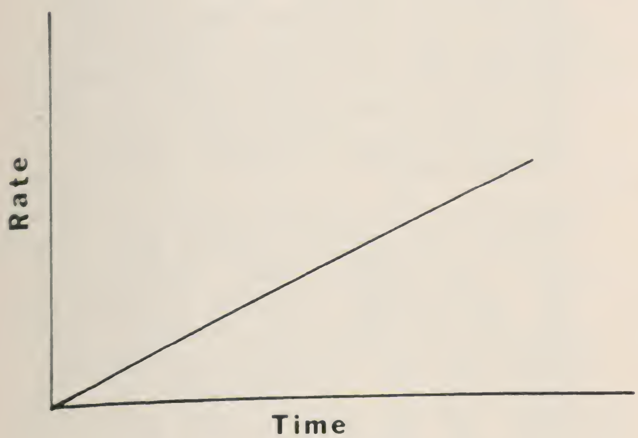
Test 1

You should find more than one correct answer to most questions.

1. In your study of the geiger counter, the following terms were used: (I) power supply; (II) window; (III) geiger tube; (IV) rate meter; (V) radioactive source; (VI) scaler; (VII) oscilloscope. The geiger counter you used for most experiments included:
(a) I, III, VII; (b) II, V, VI; (c) I, III, VI; (d) III, V, VI; (e) I, VI, VII.
2. A geiger-counter-and-scaler is to be used to study radiation given off by a weak source. The person operating the equipment should always, before beginning the study, (a) know the proper operating voltage; (b) measure the resolving time; (c) know the half-life of the sample; (d) reset the scaler before starting the measurement; (e) take a background count.
3. A piece of material consists of a single kind of atom. Which of the following statements can be made with certainty? (a) The material is a compound. (b) Each atom consists of a nucleus and an electron cloud. (c) Each atomic nucleus contains electrons, protons, and neutrons. (d) The material is an element. (e) The number of neutrons in each atom is greater than the number of protons.
4. Which of the following statements are true for radioactive atoms? (a) They are stable. (b) Negative beta radiation occurs when the nucleus has a surplus of neutrons. (c) Positive beta radiation results in an atom of higher atomic number. (d) Gamma radiation does not result in a change in the electron cloud. (e) Alpha radiation always results in a stable atom.
5. For radioactive atoms, which of the following statements can be correctly made? (a) Positive beta radiation is more common than negative beta radiation. (b) Alpha radiation requires that the electron cloud later give up two electrons. (c) Alpha radiation is most common among atoms of large atomic number. (d) Gamma radiation often follows beta radiation. (e) A normal atom of carbon-14 has six electrons in its electron cloud, and it has eight neutrons in its nucleus. (Atomic number of carbon is 6.)
6. An alpha particle from radioactive sources: (a) is more penetrating than a beta particle; (b) is less penetrating than gamma radiation; (c) has the same mass and charge as a helium nucleus; (d) has the same amount of charge as a positive beta particle; (e) moves more slowly than a beta particle of the same energy.
7. The penetrating ability of radioactive radiation: (a) is least for gamma radiation; (b) increases with increasing charge; (c) increases with increasing speed; (d) does not depend on the material through which the radiation passes; (e) increases as the ability of the radiation to ionize atoms decreases.
8. In a particular run of a counting experiment, 10,000 counts were

observed. If the experiment is repeated many times, (a) one would expect the same number of counts each time; (b) one would expect that the number of counts would generally fall between 9910 and 10,010; (c) the estimated fractional uncertainty is 0.01 for the first run; (d) the overall average is no more precise than the first result; (e) one must obtain four times as many counts in order to reduce the uncertainty to half as much.

9. In laboratory experiments which illustrate the gradual decrease in the number of counts from a radioactive source, (a) the half-life is half the time required for all the atoms to decay; (b) if the half-life is 2.5 hours, all but 1/16 of the atoms will have decayed after ten hours; (c) naturally occuring isotopes cannot be used because they always have long half-lives; (d) a plot of counting rate against time might look like the sketch.



10. In the response of a geiger counter to radioactive radiation, (a) it is important to use a power supply with a fixed voltage in order to ensure reliability; (b) the voltage pulse arises because of an ion avalanche in the geiger tube; (c) the geiger tube operates by the attraction of positive ions toward the central wire; (d) the load resistance should be small to minimize voltage loss; (e) the window is thin in order to minimize the ion avalanche.

11. The size of the voltage pulse obtained from the geiger counter depends on: (a) the kind of radiation entering the geiger tube; (b) the energy of the radiation entering the geiger tube; (c) the size of the load resistance; (d) the amount of the power supply voltage; (e) the thickness of the window.

12. A particular geiger counter has a known resolving time. Which of the following statements are true? (a) Counting rates from different sources never add up when the sources are used together. (b) Counting losses can be expected if the counting rates are high. (c) The resolving time can be computed from simple measurements. (d) If the resolving time is known, counting rates can be corrected for losses.

Test 2

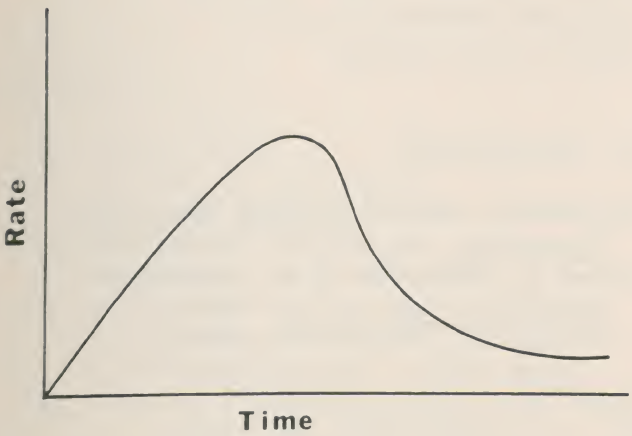
You should find more than one correct answer to most questions.

1. A geiger counter used in prospecting would differ from the one you used in most experiments in that it would include: (a) no power supply; (b) a rate meter instead of a scaler; (c) a geiger tube with a thick window; (d) a scaler instead of an oscilloscope; (e) a radioactive source.

2. Imagine that you are provided with a geiger counter of unknown characteristics, and you are instructed to use it to study high-activity sources. Which of the following operations should you perform, before beginning the study? (a) Determination of the half-life of each source;

(b) measurement of the resolving time of the counter; (c) resetting the scaler before starting each run; (d) determination of the plateau of the geiger tube; (e) checking the pulse size with an oscilloscope.

3. A piece of material is known to be a compound. Which of the following statements can be made with certainty? (a) The material is made up of molecules. (b) The material is made up of atoms. (c) Each atomic nucleus contains protons, neutrons, and electrons. (d) Each atom consists of a nucleus and an electron cloud. (e) The number of protons in the material is probably greater than the number of neutrons.
4. Which of the following statements about radioactive atoms are true? (a) Negative beta radiation occurs when the nucleus has fewer than the most common number of neutrons. (b) Some other isotope of the radioactive element is stable. (c) Gamma radiation does not change the atomic number of the radioactive atom. (d) Alpha radiation results in a decrease in atomic number. (e) Positive beta radiation requires that the electron cloud eventually lose one electron.
5. For radioactive atoms, which of the following statements are true? (a) Radioactive atoms are unstable. (b) Alpha radiation is common for atoms of low atomic number. (c) Beta radiation results in a change in the atomic number of the radioactive atom. (d) Negative beta radiation is more common than positive beta radiation. (e) A normal atom of iron-55 has 29 neutrons in its nucleus and 26 electrons in it cloud. (The atomic number of iron is 26.)
6. Beta particles from a radioactive source: (a) have more penetrating ability than alpha particles of the same energy; (b) always have the same mass as do electrons of the same energy; (c) never have the same charge as electrons; (d) are more penetrating than gamma radiation; (e) move more slowly than do alpha particles of the same energy.
7. The penetrating ability of radiation from radioactive atoms: (a) is least for alpha particles; (b) decreases with decreasing charge; (c) decreases with increasing speed; (d) increases as the ability to ionize atoms increases; (e) decreases as the density of the material being penetrated increases.
8. In a particular run of a counting experiment, 2500 counts were recorded. If the experiment is repeated many times, (a) one would not expect to obtain the same number of counts for each run; (b) the estimated uncertainty is $\pm$10; (c) the number of counts for any run could be expected to fall generally between 2450 and 2550; (d) any number of counts is equally likely; (e) the overall average would have less uncertainty than the first run.
9. Radioactive isotopes have half-lives from small fractions of a second to billions of years. Which of the following statements are valid? (a) Naturally occuring isotopes always have very long half-lives. (b) A very old sample that is still radioactive must contain atoms of very long half-life. (c) If the half-life of an isotope is 10 days, 7/8 of the original atoms will still be in the sample after 30 days. (d) If a geiger counter is used to detect the radiation, the plot of counting rate against time would appear as in the sketch on the next page. (e) The end product of a radioative chain is a stable isotope.
10. In the response of a geiger counter to radioactive radiation, (a) a voltage pulse is triggered by ionization in the geiger tube; (b) an ion avalanche will overload the geiger counter; (c) the load resistance must be large to obtain a



measurable pulse; (d) ion avalanches are triggered equally by positive and negative ions; (e) electrons are repelled from the central wire of the geiger tube because it is negatively charged.

11. The size of the voltage pulse obtained from the geiger counter is: (a) the same for beta and gamma radiation; (b) larger for higher power supply voltages; (c) independent of the energy of the radiation; (d) not dependent on the value of the load resistance; (e) smaller when the source is moved farther away.

12. Two different sources are studied by using a geiger counter. They are placed, first separately, then together, close to the window of the geiger tube, so that both individual and combined counting rates are obtained. Which of the following conclusions can be drawn? (a) The combined counting rate is the sum of the individual count rates if the individual count rates are small. (b) The combined counting rate is larger than the sum of the individual count rates if the individual rates are high. (c) The resolving time of the geiger tube can be calculated from the observed counting rates. (d) The resolving time arises from the fact that the power supply must recover from each voltage pulse. (e) It is not possible, using the counting rates, to correct for counting losses.

ANSWERS TO TESTS

(Correct or true answers are indicated)

Prerequisites Test

1. (a),(b),(d),(e)   2. (c)   3. (b)
4. (a),(b),(c),(d),(e)   5. (a)
6. (c)   7. (a),(b),(c)   8. (a)
9. (a)   10. (b)   11. (a)   12. (c)
13. (c)

Test 1

1. (c)   2. (a),(d),(e)   3. (b),(d)
4. (b),(d)   5. (b),(c),(d),(e)
6. (b),(c),(e)   7. (c),(e)   8. (c),
(e)   9. (b)   10. (b)   11. (c),(d)
12. (b),(c),(d),

Test 2

1. (b)   2. (b),(c),(d)   3. (a),(b),
(d)   4. (c),(d),(e)   5. (a),(c),(d),
(e)   6. (a),(b)   7. (a),(e)   8. (a),
(c),(e)   9. (b),(e)   10. (a),(c)
11. (a),(b),(c)   12. (a),(c)

IX LIST OF APPARATUS

The geiger counter is used in all experiments. It must have a thin window, and it should be enclosed with a power supply which has a calibrated voltage control covering the operating range of the geiger tube.

Other Equipment

Experiment A-1

Stop watch (or preset timer)
Carbon-14 source

Thallium-204 source 1
Carbon-12 rod
Assortment of absorbers (thin paper, metal foil, glass plate, lead plate)
2' connecting cable
Short connecting cables
Small portable radio
Bar magnet

Experiment A-2
Stop watch (or preset timer)
Carbon-14 source
Short connecting cables

Experiment A-3
Same as A-2 except that thallium sources 1 and 2 are used instead of the carbon-14 source.

Experiment B-1
Stop watch (or preset timer)
Americium-241 source
Thallium-204 source
Cobalt-60 source
Index card
Aluminum foil
Lead sheet

Experiment B-2
Stop watch (or preset timer)
Clock or watch (with sweep second hand)
Union Carbide Minigenerator (or other source of an isotope of short half-life)
Planchet (or other small disposable container)
Disposable rubber gloves

Experiment C-1
Oscilloscope
Cobalt-60 source
Thallium-204 source (1 or 2)
Strontium-90 source
1.5-volt battery
10-megohm resistor
0.1-microfarad capacitor
Momentary switch
4 connecting wires (short)

Experiment C-2
Thallium-204 source 1 or 2
Stop watch (or preset timer)

Experiment C-3
Stop watch (or preset timer)
Thallium sources 1 and 2
Blank source holder

X BIBLIOGRAPHY

William J. Price, Nuclear Radiation Detection, 2d edition, McGraw-Hill.

James E. Wade and G. E. Cunningham, Radiation Monitoring, USAEC, Technical Information Center (Oak Ridge, Tennessee)

PSSC film Random Events.

R. T. Overman and H. M. Clark, Radioisotope Techniques, McGraw-Hill, 1960

R. T. Weidner and R. L. Sells, Elementary Modern Physics, Chapter 9, Allyn and Bacon, 1967.

CONTENTS

I INTRODUCTION

The Guitar module covers the physics concepts, definitions, and principles of sound, wave motion and an introduction to the physics of music. The module emphasizes the following concepts and principles: longitudinal and transverse waves in an elastic medium; standing waves in an elastic medium as well as the relationship of fundamental and harmonic frequencies to the number of nodes and antinodes in a standing wave pattern; the dependence of the frequency of vibration in a string to the tension in the string, its mass, and its length; the relationship of the loudness of an audible tone to the intensity of the sound; the wave equation ($\underline{v} = \lambda \underline{f}$); the superposition of waves; dissonant and consonant musical intervals; and the musical scales.

The Guitar module is divided into three separate sections. Each section is intended to form one week of instruction, and the module can be used for one week, two weeks, or three weeks depending upon the needs and capabilities of your class.

Although this module was designed for three weeks of instruction, there are several alternative ways in which the module can be used.

	Week 1			Week 2			Week 3		
Student Characteristics	Sec.	Lab	Demo	Sec.	Lab	Demo	Sec.	Lab	Demo
High Ability	B	B-2	B-1	C-1	C-1,2	-	-	-	-
Better than Average Ability	B	B-2 Part I	B-2 Part II B-1	B,C	C-1	-	C	C-2	-
Average Ability	A	A-1	A-2	B	B-2	B-1	C	C-2	C-1
Less than Average Ability	A	A-1	A-2	B	B-2	B-1	-	-	-
Class with no math prerequisites	A	A-1	A-2	-	-	-	-	-	-

The first section is largely qualitative. The student is introduced to longitudinal and transverse waves in various media as well as the concepts of pitch and loudness. The first section is concluded with a discussion of the construction of the guitar and how it affects the production of sound in the form of the fundamental and its harmonics. Post-tests based on the goals of Section A of the module are included in Section VIII of the Teacher's Guide.

The second section of the module has the student arrive empirically (in the lab) at the relationship between the frequency of vibration of a string and its mass, length, and the tension (string equation). Section B also includes a discussion of intensity and loudness

with a development of the decibel scale of sound intensity. The section is concluded with a discussion of hearing response and a summary of the relationships and definitions covered in this section.

Section B has its own goals and post-tests which measure achievement of these goals.

Section C is a theoretical and analytical section. It derives the string equation which was found empirically in Section B. The superposition of waves is demonstrated and the consequent presence or absence of certain harmonics in plucked strings. The section is concluded with a discussion of various musical scales and then a summary of the principles and concepts learned in Section C. This section also has its own goals and post-tests.

II SPECIAL PREREQUISITES

The module presents most of the principles necessary for an understanding of wave motion, in particular, transverse waves in a taut string. There are no physics prerequisites for this module. It is assumed that the student knows how to measure length and mass in the metric system, given the proper equipment, and is able to read laboratory instruments, given proper instruction.

A recent course in high school algebra is sufficient as a math prerequisite for this module. A course in college algebra is more than sufficient.

III TABLE OF CONTENTS OF THE MODULE

Work Sheets
- Experiment A-1
- Experiment A-2
- Experiment B-1
- Experiment B-2
- Experiment C-1
- Experiment C-2

IV GOALS

The objectives of the Guitar module have been included at the beginning of each section of the module. Each objective has been stated in general terms using common words, rather than the detailed, technical language of a behavioral objective. These statements are then called goals, rather than objectives. To meet the criteria one normally expects of objectives, a sample item has been included with each goal. When a student can demonstrate to himself that he can respond correctly to any item like the one given, he knows that he has met that objective.

Section VIII of the Teacher's Guide contains tests which measure the achievement of samples of the goals from each section. These tests can be used to evaluate student performance, weekly, or at the end of two weeks, or at the conclusion of their study of the entire module. A statement of these goals follows:

1. Understand how the details of guitar construction and how it is played affect its loudness, pitch, and quality.
2. Understand the concept of elasticity and how the elasticity of a material affects its vibrations.
3. Understand what is meant by the fundamental and its harmonics, and how these can be produced in a string fixed at both ends.
4. Know how the pitch and quality of sound are related to string vibrations.
5. Know the mathematical relationship between fundamental frequency of a vibrating string and tension, length, and mass.
6. Know the definitions of power and intensity.
7. Understand the concept of intensity level.
8. Understand the whole-population hearing ability curves (Figure 27).
9. Understand the concept of loudness level.
10. Understand how the superposition of two traveling waves produces a standing wave.
11. Know the relationship between the speed, wavelength, and frequency of a wave.
12. Know the general formula for the frequencies of the normal modes of oscillation of a string which is fixed at both ends.
13. Understand how the superposition of harmonics on a string produces any particular standing wave.
14. Understand the physical basis of musical intervals, consonance, dissonance.

V DISCUSSION OF ACTIVITIES

a. Laboratory Activities

Experiment A-1. The Guitar and Its Sounds

The purposes of this experiment are: to demonstrate to the student the transverse and longitudinal modes of vibration in a coiled string or spring, what parts of a vibrating system contribute to the sound we hear, and how the sound of a guitar string is affected by the way in which it is plucked.

The apparatus needed for one set-up of Experiment A-1 is as follows:

Item	Quantity
Guitar (tuned)	1 (2 would be helpful, so that one remains tuned at all times)

Item	Quantity
Small Transistor Radio	1
Tin cans with wire connecting the bottoms of the cans	2
Long helical spring	1
Guitar picks	1

Experiment A-2. Harmonics and Modes of Oscillation

The purpose of this experiment is to demonstrate the presence of harmonics in the vibrations of the guitar strings and the relationship of nodes and antinodes to the presence or absence of certain harmonics. This experiment is probably best accomplished through a demonstration.

The apparatus needed for one set-up of Experiment A-2 is as follows:

Item	Quantity
Guitar	1
Long helical spring	1

Experiment B-1. The String Equation

The purpose of this experiment is to determine the relationship between fundamental frequency and the length, mass, and tension of a vibrating string.

The apparatus needed for one set-up of Experiment B-1 is as follows:

Item	Quantity
Guitar	1
Audio Oscillator	1
Speaker	1
Spring Scale	1
Pulley	1
Weights & Weight Hanger	1 set
Guitar Capo (clamp)	1

Experiment B-2. Loudness and Resonance

The purposes of this experiment are: to determine the relationship between amplitude and loudness of a sound wave, and to demonstrate the presence of body resonances which match the string frequencies. It might be appropriate to perform Part II on resonances as a classroom demonstration.

The apparatus needed for one set-up of Experiment B-2 is as follows:

Item	Quantity
Guitar	1
Audio Oscillator	1
Speaker	1
Microphone	1
Oscilloscope	1
Decade Resistance Box	1
Push-Button Switch	1
Sound Level Meter	1
Cork Dust	
Acoustic Transducer	1

Experiment C-1. Transverse Pulses on a Spring

The purposes of this experiment are: to observe the properties of a pulse or wave traveling in a guitar string or stretched spring and to observe the superposition of two different pulses traveling in the same medium. The purposes of this experiment are perhaps best accomplished by means of a classroom demonstration.

The apparatus needed for one set-up of Experiment C-1 is as follows:

Item	Quantity
Long Helical Spring	1
Stopwatch	1

Experiment C-2. Guitar Scales

The purpose of this experiment is to observe the even-tempered scale of a tuned guitar.

The apparatus needed for one set-up of Experiment C-2 is as follows:

Item	Quantity
Guitar	1
Meter Stick	1

b. Other Activities

The Guitar module has been designed for use in an introductory physics course which has two or three hours of laboratory time per week and three fifty-minute classes per week. Some of the experiments are quite long and probably

cannot be finished in one laboratory period. For lower ability students, many of the experiments should be done as classroom demonstrations, especially Experiment A-2, Part II of Experiment B-2, and Experiment C-1.

Physics of Technology modules can be used most effectively if you avoid lectures entirely. Class time can be most interesting and helpful to students if you will spend that time doing demonstrations, discussing the laboratory work, and asking students about questions and problems in the module. A list of resource material is included at the end of this section.

C. Resource Materials

A. <u>16-mm Sound Films</u>
1. "Sound Waves and Their Sources"; Encyclopaedia Britannica Educational Corp., Chicago, Ill.
2. "Quality of Musical Sounds"; E.B.E.C.
3. "Waves in a String"; McGraw-Hill Textfilm, New York, N.Y.
4. "Sound Waves"; Educational Foundation for Visual Aids, Surrey, England.
5. "Standing Waves"; Sargent-Welch Sci. Co., Skokie, Ill.
6. "Vibratory Motion and Waves"; Michigan State Univ., East Lansing, Mich.

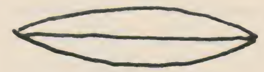
B. <u>8-mm Film Loops</u>
1. "Transverse Standing Waves in a Spring", E.B.E.C.
2. "Reflection of Waves in a Spring", E.B.E.C.
3. "Single Pulses in a Spring", E.B.E.C.
4. "Superposition of Pulses in a Spring", E.B.E.C.
5. "Longitudinal Nature of Sound Waves", Gateway Educ. Films Ltd., London, England.
6. "A Wave Equation", Gateway.
7. "Sound-Frequency and Pitch", United World Films, Inc., New York, N.Y.
8. "Sound-Musical Quality", W.F.I.

C. <u>Transparencies</u>
1. Sympathetic Vibrations, Z-8662-035, Lapine Sci. Co.
2. Major Scale Octave, Z-8662-036, Lapine.
3. Test Tube Musical Scale, Z-8662-037, Lapine.
4. Piano Vibration Rates, Z-8662-038, Lapine.

VI SAMPLE DATA

<u>Experiment A-1</u>
1. No. Fades away quickly.
2. The vibrating thumb is louder.
3. Thin light objects like cabinet doors, windows, or waste cans.
4. Near the bridge.
5. It is vibrating. The vibrations can be felt and their sound diminishes.
6. Yes. Yes it stops the sound. Yes you can stop the sound. The vibrations must be transverse.
7. Plucking perpendicular to the sound board is loudest.
8. The pitch goes up as you shorten the strings. Same for all strings.
9. The sound is louder with the pick.
10. The sound is more hollow when the hole is covered.
11. More hollow.
12. Lower pitch strings are emphasized more.
13. Yes.
14. Increasing the tension increases the pitch.
15. Tensions were about the same.
16. The larger the diameter the lower the pitch.

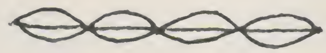
<u>Experiment A-2</u>
1.



2. The same
3. No.
4. No.
5. The pitch is higher.

6. 
7.

8. The Same.
9. No.
10. Second harmonic frequency is double that of the first harmonic.
11. No.
12. It is higher.
13. Yes.
14. 

15. Frequency is 3 times that of first harmonic.
16. Frequency is 4 times that of first harmonic.
17. 1/4 the length of the string.
18. No.
19. 

20. Each harmonic is a number of times the fundamental.
21. Higher.
22. No. The vibrations dampen out.
23. Not able to produce it.
24. Frequency would be five times the first harmonic.
25. By touching the string 1/6 or 1/7 of the length of the string.
26. Yes.
27. Yes. In the middle.
28. At one third of the length.

Experiment B-1

1-10.

Table 1.

T = 58.8 N L = 0.65 m

String	Frequency (Hz)	Total Mass (kg)	Total Length (m)	Mass (kg) / Length (m)	Vibrating Mass (kg)
low E	62	0.0096	0.95	1×10^{-2}	6.5×10^{-3}
A	74	0.0069	0.95	7.2×10^{-3}	4.7×10^{-3}
D	110	0.0027	0.79	3.4×10^{-3}	2.2×10^{-3}
G	146	0.0022	1.0	2.2×10^{-3}	1.4×10^{-3}
B	150	0.0011	1.0	1.1×10^{-3}	7.2×10^{-4}
high E	200	0.0008	1.0	8.1×10^{-4}	5.3×10^{-4}

11-13.

Table 2.

m = 0.0021 kg L = 0.59 m

m/L = 0.0035 kg/m

	Frequency (Hz)	Tension (N)
1 kg	100	9.8
2 kg	130	19.6
3 kg	160	29.4
4 kg	180	39.2
5 kg	200	49.0
6 kg	220	58.5

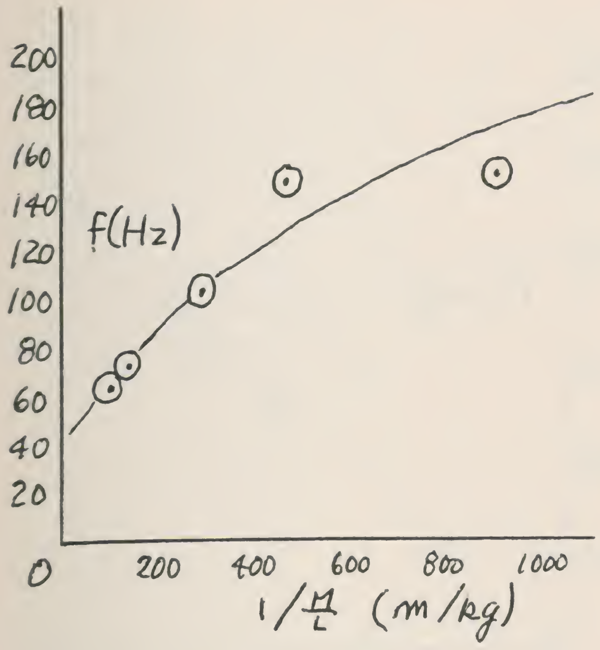
14-15.

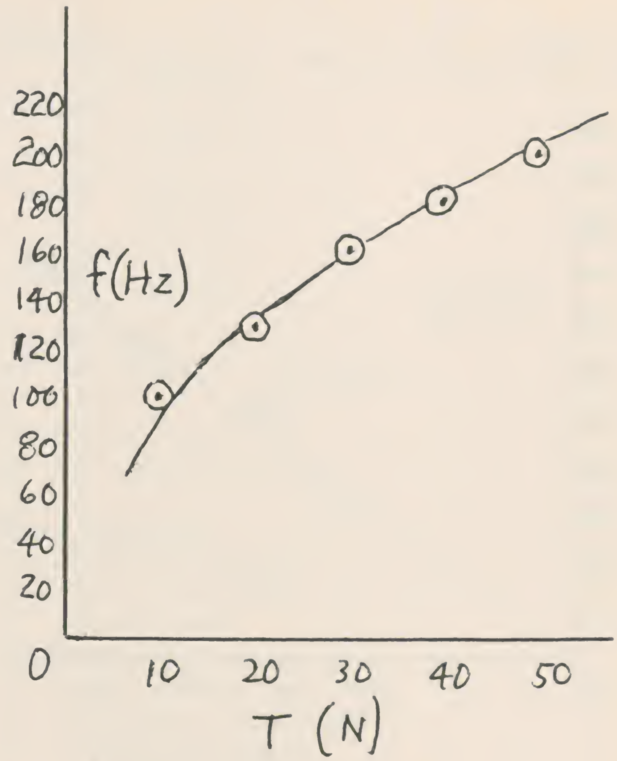
Table 3.

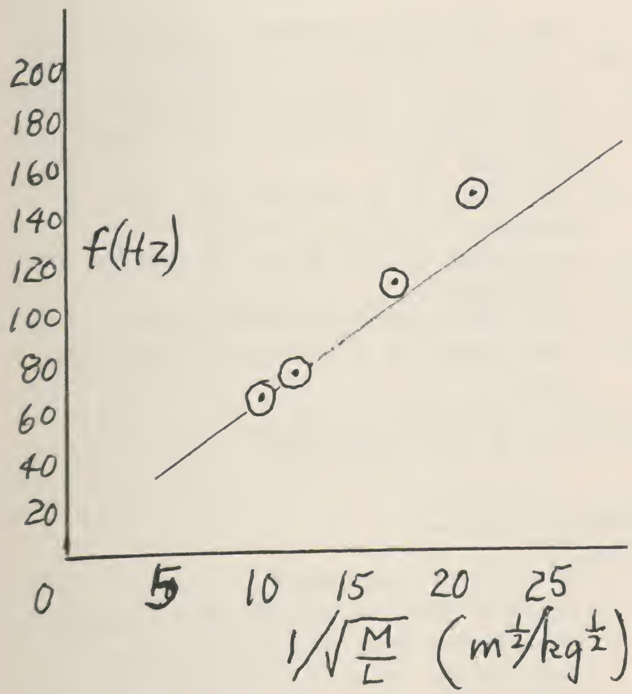
T = 68.3 N m/L = 6.5×10^{-4} kg/m

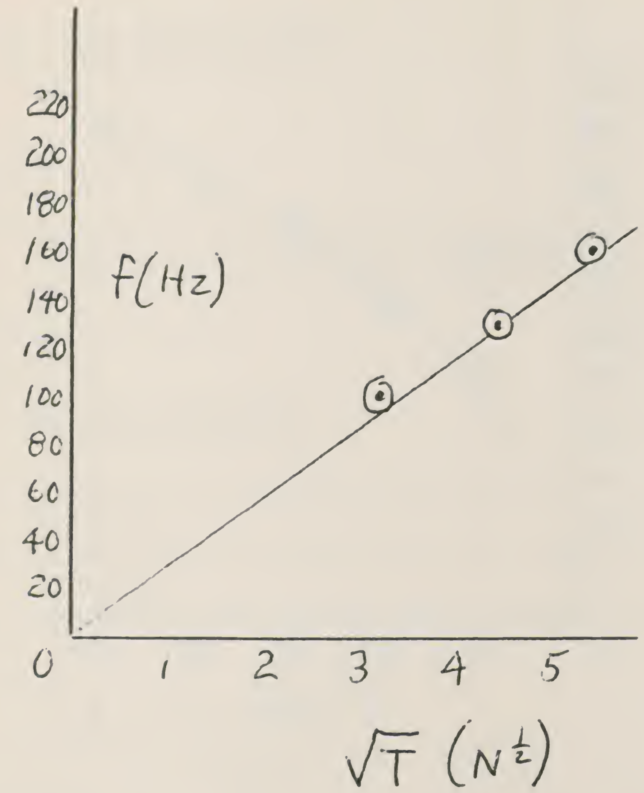
Frequency (Hz)	Length (m)
250	0.65
308	0.54
357	0.46
476	0.38
588	0.32

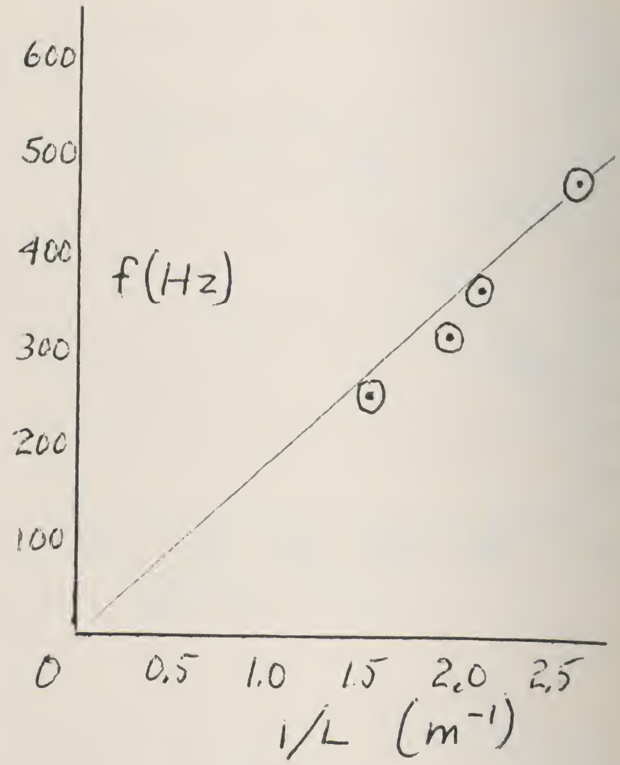
16. Decreases
17. See graph on page 151.

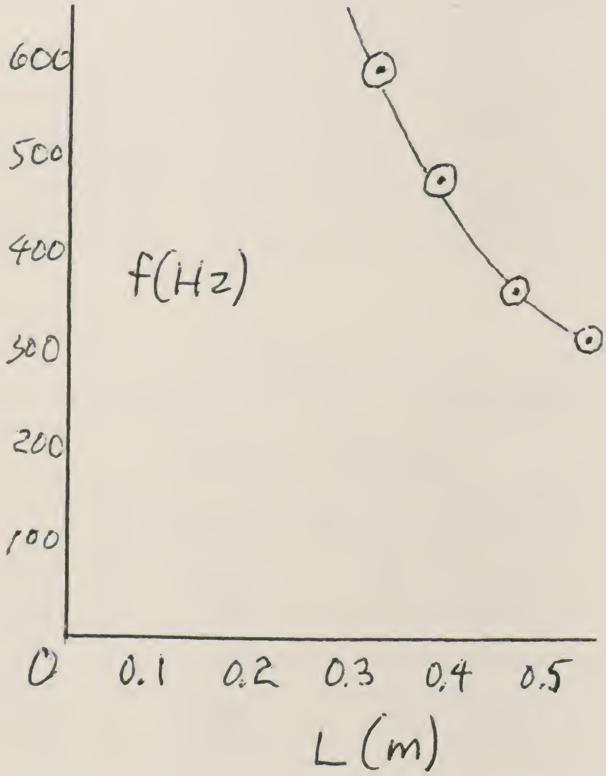

200
180
160
140
120
100
80
60
40
20
0
f(Hz)
200
400
600
800
1000
1/M/L (m/kg)


220
200
180
160
140
120
100
80
60
40
20
0
f(Hz)
10
20
30
40
50
T (N)


200
180
160
140
120
100
80
60
40
20
0
f(Hz)
5
10
15
20
25
$1/\sqrt{\frac{M}{L}}$ ($m^{\frac{1}{2}}/kg^{\frac{1}{2}}$)







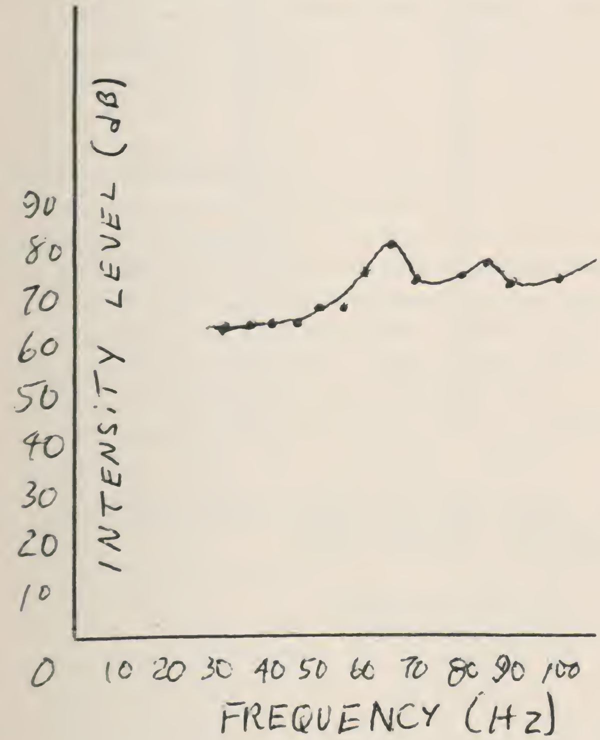
18. The plot of $\underline{f}$ versus $1/\sqrt{\underline{m}/\underline{L}}$.
19. $\underline{f} = 5.7\ kg^{\frac{1}{2}}m^{-\frac{1}{2}}s^{-1} \cdot 1/\sqrt{\underline{m}/\underline{L}}$.
20. Increases. Almost a straight line for larger tensions. See graph on page 151.
21. The plot of $\underline{f}$ versus $\sqrt{\underline{T}}$. See graph.
22. $\underline{f} = 29.3\ s^{-1}N^{-\frac{1}{2}}\sqrt{\underline{T}}$.
23. Decreases.
24. No. See graph on this page.
25. See graph of $\underline{f}$ versus $1/\underline{L}$ on this page.
26. $\underline{f} = 185\ ms^{-1} \cdot 1/\underline{L}$.
27. $\underline{f} = \underline{K}(1/\underline{L})(\sqrt{\underline{T}})(1/\sqrt{\underline{m}/\underline{L}})$.

<u>Experiment B-2</u>

<u>Part I</u>

1. The pitch increases.
2. Around 3000 Hz sounds the loudest.
3. Yes. Same for all frequencies. Amplitude seems to increase as the pitch increases.
4. Yes.
5. 0.85 open, 0.80 closed.
6. 0.723 open, 0.64 closed.

7. 4.0 open, 3.8 closed.
   $4^2 = 16.0$ open, $(3.8)^2 = 14.4$ closed.
8. Low level difference = 0.08.
   Louder level difference = 1.6.
9. Low level ratio = 1.13.
   Louder level ratio = 1.11
10. 3.0 open, 2.8 closed.
    $(3.0)^2 = 9$ open, $(2.8)^2 = 7.8$ closed.
11. 3-kHz difference = 0.08.
    400-Hz difference = 1.2.
12. 3-kHz ratio = 1.13
    400-Hz ratio = 1.15.



Part II

1. 3 resonances. 64 Hz, 88 Hz, 125 Hz.
2. $\underline{f}_{EE} = 160$ Hz
   $\underline{f}_{AA} = 220$ Hz
   $\underline{f}_{G} = 400$ Hz
   $\underline{f}_{B} = 500$ Hz
   $\underline{f}_{E'} = 600$ Hz
3. About 100 Hz.
4. See graph on this page.
5. Yes.
6. About 5 Hz.
7. The sound board.

Experiment C-1

1. About 1 second.
2. About 1 second.
3. About 1 Hz.
4. Same.
5. Shape change is slow.
6. Amplitude decreases.
7. a. Opposite side.
   b. Shape is the same.
8. Nearly the same.
9. Nearly the same.
10. Greater than. Amplitude is about twice that of original pulses.
11. Same.
12. The pulses cancel each other out.
13. Yes.

Experiment C-2

Table VIII.

Fret No.	Distance From Fret to Bridge (in cm)	Frequency of a String Stopped at Fret (in Hz)	Ratio of This Frequency to Previous Frequency (Round to 3 Figures)
0 (open)	64.0	220 ($\underline{f}_o$)	
1	61.1	234	1.06
2	57.7	249	1.06
3	54.4	264	1.06
4	51.4	278	1.05
5	48.5	295	1.05
6	45.7	313	1.06
7	43.1	333	1.06
8	40.7	351	1.05
9	38.4	371	1.05
10	36.2	394	1.06
11	34.2	418	1.06
12	32.3	443	1.05
13	30.5	469	1.05
14	28.7	497	1.06
15	27.0	530	1.06
16	25.5	561	1.05
17	24.2	596	1.06
18	22.7	629	1.05
19	21.5	665	1.05
20	20.2	706	1.05

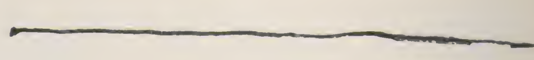
1. Yes.
2. Yes.
3. Yes. The 12th fret.
4. 12.
5. Yes for each harmonic. They are the 7th fret for the third harmonic, the 5th fret for the fourth harmonic, and the 2nd fret for the ninth harmonic.
6. Yes, they are an octave apart.

VII. SOLUTIONS TO PROBLEMS

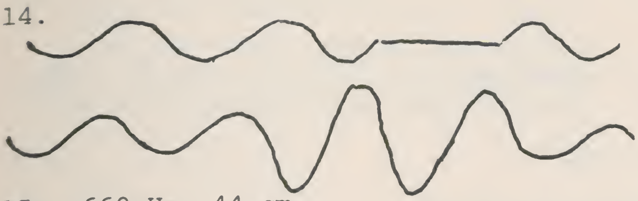
The problems and questions are an important part of the module. Questions should be discussed in class, in so far as possible. Many of the problems should be discussed in class, but if answers are provided, many students will work the problems outside of class and check their own work. The problem answers below are provided so that you can copy them and distribute them to students, if you wish.

1. -
2. ≃ 0.5 for each.
3. smaller, 1/4.
4. 2×10^{-5} W.
5. 5×10^{-9} W.
6. -
7. 12 bels.
8. 1.51 bels, 15.1 dB.
9. 3.16×10^{-7} W/m^2.
10. -
11. 10 phons.
12. 82 dB.
13. a.

b.



14.



15. 660 Hz, 44 cm.
16. -
17. -
18. D:C = 9:8, E:C = 5:4, F:C = 4:3, G:C = 3:2, A:C = 5:3, B:C = 15:8, C:C = 2:1.
19. F:E = 16:15 = 1.06666, C:B = 16:15. Twelve times that factor will not produce a factor of 2 needed to obtain the octave.

VIII. POST-TESTS

<u>Section A - Test 1</u>

1. Plucking an open guitar string over the sound hole produces a tone containing many harmonics. How could you produce a tone from this same string that did <u>not</u> contain the 2nd harmonic? How would this sound differ from the original sound?
2. Plucking the lowest string of a guitar six or seven inches from the bridge produces a sound of certain pitch and quality. Using the same guitar, how could you produce a sound of higher pitch but with the same quality?
3. The soundboard of a guitar vibrates naturally with certain nodes and antinodes. Would you attach the bridge to a node or antinode? Why?

<u>Test 1 - Answers</u>

1. Pluck the string in the middle. The sound would be more hollow.
2. Shorten the string by pressing it against one of the frets and pluck it a little closer to the bridge.
3. It should be at an antinode because the node is a point of little or no vibration.

<u>Section B - Test 1</u>

1. A guitar string has a fundamental frequency of 164 Hz. If this string is replaced by a string having four times more mass, and if the tension is one ninth as great, what will be the frequency of the new string?
2. What is the frequency of the 5th harmonic of a string 60 cm long whose mass is 30 grams and which is under a tension of 180 newtons?
3. A guitar string is plucked by a sharp pick 1/3 of the distance from the bridge to the nut. What harmonics are missing? Sketch a graph for each harmonic, showing the relative amplitude and frequency of each one that is present.
4. The fundamental frequencies of three musical notes are as follows: 1 = 330 Hz, 2 = 660 Hz, 3 = 360 Hz. Which notes are consonant? Why?

<u>Test 1 - Answers</u>

1. 27.3 Hz.
2. 250 Hz.
3. 3rd, 6th, 9th, etc.
4. 660 and 330 Hz because they are in the ratio of 2:1.

<u>Section B - Test 2</u>

1. The 6th string of a guitar has four times the mass per unit length of the 3rd string. The two strings have the same tension and length. What will be the frequency of the 3rd string if the 6th string has a frequency of 165 Hz?
2. A string vibrates with a frequency of 100 Hz when the tension is 10 newtons. What must the tension be for the same string to vibrate with a frequency of 400 Hz?
3. An open guitar string vibrates at 330 Hz when its length is 75 cm. A guitarist shortens the string to 50 cm. What is the frequency of vibration?

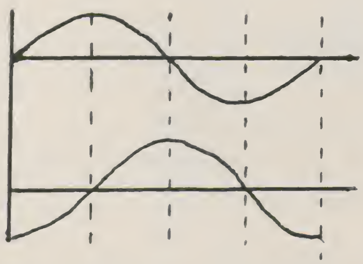
4. Sound of power 2×10^{-6} watts falls on an eardrum of area 1×10^{-4} m^2. What is the sound intensity at the eardrum?
5. Sound of an intensity of 10^{-2} W/m^2 is produced by a jet airplane taking off. What is this intensity level in dB? (The minimum audible intensity is 10^{-12} W/m^2.)

<u>Test 2 - Answers</u>

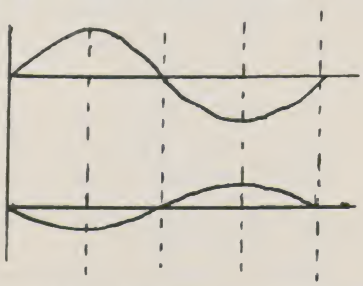
1. 330 Hz.
2. 160 N.
3. 495 Hz.
4. 2×10^{-2} W/m^2.
5. 100 dB.

<u>Section C - Test 1</u>

1. The two sound waves shown below reach your ear at the same time. What does the result of the two waves look like? (Graph the result.)



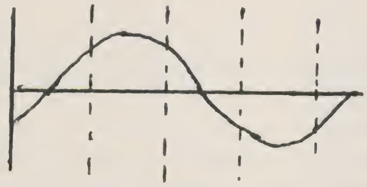
2. The two sound waves shown below reach your ear at the same time. What does the result of the two waves look like? (Graph the result.)



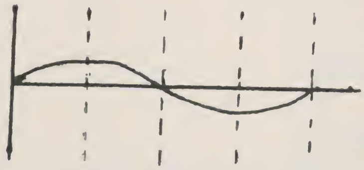
3. Using the frequencies of Table IV of Section C in the module, would you say that B and C above middle C (C') are consonant or dissonant? Why?
4. A radio station operates at a frequency of 710 kHz. What is the wavelength of the radio wave? (The speed of the radio wave is 3×10^8 m/s.)

<u>Test 1 - Answers</u>

1.



2.



3. They are dissonant because the difference frequency is 33 Hz.
4. 423 m.

<u>Section C - Test 2</u>

1. A guitar string 75 cm long vibrates with a fundamental frequency of 220 Hz. What is the wavelength of this fundamental?
2. A wave of frequency 310 Hz has a wavelength of 20 cm. What is the speed of the wave?
3. Sounds of 440 Hz and 456 Hz are mixed together. What beat frequency would be heard?
4. A guitar string 75 cm long vibrates with a fundamental frequency of 220 Hz. What are the frequency and wavelength of the third harmonic?

<u>Test 2 - Answers</u>

1. 150 cm.
2. 6.2 m/s.
3. 16 Hz.
4. $\underline{f}$ = 660 Hz, λ = 50 cm.

IX. LIST OF APPARATUS

Most of the equipment needed in this module is considered to be "normal" lab equipment and no source is listed for such items.

Item	Quantity	Source
Guitar	1 (2 would be helpful, so that one remains tuned at all times.)	
Guitar Pick	1	
Small Transistor Radio	1	
Tin Cans (with wire connecting)	2	
Long Helical Spring	1	
Audio Oscillator	1	
Speaker	1	
Spring Scale	1	
Pulley	1	
Weights with Weight Hanger	1 set	
Guitar Capo (clamp)	1	
Microphone	1	
Oscilloscope	1	
Decade Resistance Box	1	
Push-Button Switch	1	
Sound Level Meter	1	
Cork Dust		
Acoustic Transducer	1	Any local electronics store
Stop Watch	1	
Meter Stick	1	

CONTENTS

I INTRODUCTION

Hydraulic Devices refers to a variety of common devices whose operation can be well understood in terms of the basic physics of static and dynamic fluids. The module considers such devices as the hydraulic jack, the barometer, the siphon, the aspirator, the sphygmomanometer, and the pitot tube. These devices are used as a vehicle for the study of physical concepts and laws such as density, specific gravity, pressure, Pascal's Law, pressure measurements, gauge and absolute pressures, mechanical advantage, efficiency, buoyancy, Archimedes' principle, and Bernoulli's equation.

II SPECIAL PREREQUISITES

No special prerequisites are required. The concepts of force, torque, and equilibrium are treated very briefly, or left to the students' intuitive understanding. As required, at the appropriate place the instructor may wish to review these concepts. A brief review appendix is included on the concepts of work and energy.

III TABLE OF CONTENTS

IV GOALS

The goal of the module is to develop understanding of the following:

1. Density of materials.

2. Properties of liquids.

3. The relationship between force and pressure.

4. The way in which pressure increases with depth in liquid.

5. The way in which pressure is transmitted through fluids.

6. Pressure measurements.

7. The mechanical advantage and efficiency of hydraulic jacks.

8. The buoyant forces exerted on objects by liquids.

9. The way in which pressure depends on the rate of flow of a liquid.

V DISCUSSION OF ACTIVITIES

In using this module you will find that the authors have, when faced with a choice between expanding the material covered for completeness or omitting some detail, chosen to simplify the coverage. We have attempted to stick to the central topics, leaving it up to the instructor to introduce material for additional coverage when he thought it appropriate or relevant.

Some places where you may wish to expand the coverage given or use the text as an opportunity to extend or review knowledge the students have previously acquired include:

1. Work and energy and Bernoulli's equation.
2. Temperature dependence of density, volume expansion of solids.
3. Hydropower-generated electrical energy, energy as a limited resource, turbines, hydrologic cycle.
4. Fluidics, fluidic amplifiers, switches, etc. See for example: –Respiratory Theory, May 1973, p. 29, Barrington Publications.
5. Gaseous fluid applications using Bernoulli's effect.
6. Water Ram as an example of many technological applications which lower the average kinetic energy of some matter while raising the potential energy of a fraction of the matter.

Laboratory Experiments

Because of the variation in laboratory scheduling in different schools, we have tried to select a set of laboratory exercises that would provide for some versatility in terms of time requirements. Many of the exercises can be done as demonstrations and will easily fit into a conventional 50-minute period.

Note that the instructions contain little on general laboratory techniques. We have left it to the instructor to provide guidance on laboratory report format, discussion of errors, etc. Only one experiment includes a few problems at the end. Again, the instructor retains the option of adding numerical calculations to the experiment.

The time estimates given are only approximate. The time requirement depends very much on the direction and assistance given by the instructor and by the amount of work the instructor sets for completion in the laboratory as opposed to outside of the laboratory. The times listed are based on the needs of a "slow" student. You may choose to do some of the experiments as demonstrations.

Experiment A-1: Devices

This is intended to be an exploratory exercise to provide the students with an early opportunity to put their hands on a simple hydraulic tool and view other hydraulic devices. The exercise attempts to raise many questions and thus motivate the students to work into the module. The siphon and the aspirator should be demonstrated here. Estimated time: 1 hour.

Experiment A-2: Hydrometry

Part A is a rather conventional "hands-on" use of a simple device. Part B uses an automotive hydrometer to reinforce the students' understanding of density and specific gravity. Observations relevant to Archimedes' Principle are made before the topic is treated in the text. This makes it easier for the student to understand the section on buoyancy. Estimated time: 2 hours.

Experiment B-1: Pressure Dependence on Depth

A vertical water column is used to simulate a water distribution system. Some caution should be exercised by the instructor since the force measurements are made with spring balances calibrated in units of grams. Pressure is calculated from force and area measurements. The density is obtained by taking the slope of a best straight line fit to plotted data points. Some assistance in this technique may be required. Since the flexible diaphragms are fragile and not too securely attached, this may be a rather "wet" experiment. Estimated time: 1 hour.

Experiment B-2: Measuring Density

Density determinations are made by several techniques including using Archimedes' Principle. The time estimate does not include problem solving. Estimated time: 2 hours.

Experiment B-3: A Closed Hydraulic System

A two-piston hydraulic system is simulated using two glass hypodermic syringes of differing diameter. Input forces are applied with slotted weights, and the output force is measured with the spring compression balance. The range of input forces is limited by a concern for safety. We suggest not having too many slotted weights suspended where they might fall and produce a foot injury. With that limitation on forces, the friction of the apparatus is a considerable component leading to fairly low average efficiency ($\sim 50\%$). The apparatus can be used with either light oil or water as the hydraulic fluid; each has some advantages and some disadvantages. Dust stuck on the oil can be a significant problem. Most ground-glass syringes require some break-in period. Estimated time: 1 1/2 hours.

Experiment C-1: The Bernoulli Effect

Ten examples of the Bernoulli effect are included. No quantitative results are obtained.

Experiment C-2: Blood Pressure Measurements

A brief investigation of the use of a sphygmomanometer. Opportunity to introduce some biophysics or biology exists. High accuracy will be difficult to obtain without experience. Exercise produces the most rapid change in blood pressures. Estimated time: 1/2 hour.

Demonstrations

This module is unusually adaptable to the use of qualitative demonstrations using real devices. The two-cylinder demonstration system with brake light and oil light switches that is used in Experiment A-1 was originally intended for demonstration, but fitted more naturally into the experiment. Many instructors who construct other demonstration apparatus will find that it also can be naturally incorporated into the module.

1. A simulated auto braking system makes a nice demonstration that is inexpensive and of interest to the students. The brakes from a wheel of an auto, together with the backing plate, can be gotten inexpensively from a junkyard. You might want to get two, a disc-type and a drum-type. The brakes can be mounted on a board and connected by brake tubing to either a used master cylinder (without power assist) or just a simple hydraulic cylinder of any kind. The students can observe the actual operation of the brakes, especially if they can remove the drum from the drum brakes.

2. Bernoulli's Effect. A pitot tube can be inserted through the wall of a tubing system carrying a flow of water. Qualitative results can be shown using an open manometer of tygon tubing. Quantitative results are poor ($\sim$ 50% error) because of non-streaming flow in the tube. Manufacturer of Pitot tube: Dwyer Instruments, P.O. Box 373, Michigan City, Indiana, 46360.

3. Various conventional demonstrations of Bernoulli's Effect using air can be done.

a) Pick up a piece of paper by blowing through a straw.
b) Ping-pong ball on the output of a vacuum clearner.
c) Discuss airplane lift, shower curtain effects, etc.

Sources of Equipment

Cenco, Welsh, and Edmund Scientific all offer inexpensive demonstration equipment.

"Physics Demonstration Experiments", Vol. 1 by Harry Meiners, The Ronald Press, New York, contains several suggestions for classroom demonstration.

Audio-Visual Suggestions:

1. Overhead transparencies.
   Basic Fluid Power - Book I
   McGraw-Hill
   Approximate cost: $85.
   Comments: Nine of the first ten transparencies could usefully augment conventional lecture presentations related to this module. The last four transparencies relate to the Gas Laws and Temperature scales and look quite useful (but not for this module).

2. Slides.
   Meeting Guide No. 21 ($9).
   Meeting Guide No. 22 ($7).
   Caterpillar Tractor Co., Peoria, IL
   Service Training Division.
   These two service training guides consist of a script (of not much value) and a large number of slides, many of which would enhance the presentation of this module. Meeting Guide No. 21, Principles of Basic Hydraulics, contains 50 slides (2" x 2"). Meeting Guide No. 22, Putting Hydraulics to Work, contains 35 slides (2" x 2"). More than half of these could be used. One alternative to consider: the instructor may wish to write his own script to supplement a collection of these slides, and thus provide his students with an alternative learning resource.

VI SAMPLE DATA

Exp. A-1. A mechanical advantage of approximately 40 should be obtained. The spring balance will indicate about 5 lbs. to lift a person on the jack.

Exp. A-2. Most supermarket fluids have S.G. near to 1.0. Oils will be lower. Alcohol-containing solutions are also less than 1. Maple

syrup, antifreeze, liquid soaps, vinegar, etc. are acceptable. The automobile hydrometer balls have density 1.014, 1.032, 1.048, and 1.059 g/cm^3.

Known Liquids

Liquid	Known Specific Gravity	Measured Specific Gravity
Water	1.000	.995
Vinegar (5% acetic)	1.002	1.0055
Glycerol 96%	1.250	1.2508
Liquid detergent	1.095	
Pancake syrup	1.323	

Sugar Solution
Range of Specific Gravity

From 1.00 to 1.15

Comparison of experimental values for freezing points of antifreeze solution to freezing point indicated by container label.

Protection to (°F)	Percentage Experimental	Percentage from Container
+30°		
+15°	23	21
0°	33	33
-15°	44	42
-30°	50	48

Exp. B-1. Should produce $\rho=1.0$ g/cm^3 ± 5%. This experiment produces a relatively accurate result with some rather cheap instruments (meterstick, for example).

Data Table

Port	Spring Balance Reading (g)	Force (dyn)	Depth (cm)
1	125	$1.23x10^5$	32.5
2	225	$2.21x10^5$	66.5
3	350	$3.43x10^5$	101.5
4	450	$4.41x10^5$	135.5

Slope of the Graph

a. From your graph, find the values of pressure and depth at two points (use two points on the line you draw, not two actual data points):

$P_1 = 0.43x10^5$ (dyn/cm^2)

$P_2 = 1.50x10^5$ (dyn/cm^2)

$h = 40$ (cm)

$h = 140$ (cm)

b. Calculate the rise and the run:

Rise $= P_2 - P_1 = 1.07x10^5$ dyn/cm^2

Run $= h_2 - h_1 = 100$ cm

c. Calculate the slope:

$$\text{Slope} = \frac{\text{rise}}{\text{run}} = \frac{P_2 - P_1}{h_2 - h_1}$$

$$= 1.07x10^3 \ dyn/cm^3$$

$$(\rho = \frac{D}{g} = 1.09 \ g/cm^3)$$

Exp. B-2. Densities calculated using the graduated cylinder measurement of volume will be less accurate than those calculated from the measurement of the apparent loss of weight when submerged in water. Density volumes for common substances can be found in the Handbook of Physics and Chemistry.

Finding Density from Displaced Volume

Mass of Object (g)	Volume of Water in Graduated Cylinder (cm^3)	Volume of Water plus Object (cm^3)	Volume of Object (cm^3)	Density of Object (g/cm^3)
200.0 (Brass weight)	450	474	24	8.3
13.1 (Rubber stopper)	450	461	11	1.2
23.7 (Plastic cylinder)	450	467	17	1.4

A More Accurate Measure of Density

	Object No. 1	Object No. 2
Mass in air $\underline{M}_A$ (g)	200.0	13.1
Apparent mass in water $\underline{M}_W$ (g)	176.6	2.5
Volume $(\underline{M}_A - \underline{M}_W)/(1\ g/cm^3)$ (cm^3)	23.4	10.6
Density $\rho\underline{x}$ (g/cm^3)	8.55	1.24

Objects Which Float

	Object No. 1	Object No. 2
Mass of object in air $\underline{M}_A$ (g)	(Pressed wood) 120.8	(Styrofoam) 2.1
Apparent mass Object in air plus sinker in water $(\underline{M}_A + \underline{M}_{SW})$ (g)	208.8	90.4
Apparent mass Both object and sinker in water $(\underline{M}_W + \underline{M}_{SW})$ (g)	39.9	11.5
Volume of object $[(\underline{M}_A + \underline{M}_{SW}) - (\underline{M}_W + \underline{M}_{SW})]/(1\ g/cm^3)$	168.9	78.9
Density $\rho\underline{x}$ (g/cm^3)	.715	.027

Exp. B-3.

D_1 = 1.49 cm. (10-cc syringe)

D_2 = 2.27 cm. (30-cc syringe)

IMA = 2.31

Exp. C-2. In a person at rest, the systolic pressure should be in a range from 100 to 130. The diastolic pressure should fall in a range from 70 to 90.

VII SOLUTIONS TO PROBLEMS

Section A

1. 40 lbs/ft^3
2. 25.77cm^3
3. 18,667 lbs.
4. 2.62 g/cm^3 163 lbs/ft^3
5. 754 ft^3
6. 1870 gallons
7. 1.2 g/cm^3

Section B

1. 625 feet
2. The floating ice cube has displaced a volume of water whose weight just equals the weight of the ice cube. When the ice melts, it turns into water whose volume just equals the displaced volume. Therefore, no overflow.
3. Lower in the gin (less dense than water). Ice will not float in pure alcohol.
4. No, it will go down slightly, assuming that the book sinks. The weight of the book on the floating raft was already supported by a buoyant force caused by a displacement of pool water. The sunken book will displace less water. If the book floats, its weight is still supported by displacing water and the level will remain the same.
5. Result depends on experimental data.
6. IMA = 20; 500 strokes.
7. Assuming standing on one heel (area .35 in^2). Yes, = 300 PSI, which is greater than 250 lbs/in^2 breaking strength.
8. a) P = .0977 lbs/in^2.
   b) Buoyant force = 1.17 lbs.
   c) 2.4 in^3.
9. 50 lbs.
10. a) 11.76 lbs.
    b) 1330 lbs.
11. a) 339 ft.
    b) 14,700 lbs.
13. 337.5 ft.
14. 5120 lbs/ft^2.
15. No, flow will only support 83 lbs.
16. 1 in^2/tire.
17. 1.5 lb/in^2; 160 tons.
18. Girl is more dense, 1.011, 1.017.

Section C

1. a) at surface P_G = 10 lbs/in^2
   P_A = 24.7 lbs/in^2.

   at bottom P_G = 11.74 lbs/in^2
   P_A =26.4 lbs/in^2.

   b) 41.6 feet/sec.
2. 3.2 x 10^8 Joules/sec.
3. 1 foot.
4. 1500 gal/hr.
5. Over 20 hours.
6. 2.7 lbs/in^2.
7. 8 x $10^{-5} in^2$.
8. a) 54.3 ft/sec.
   b) 49.4 ft/sec.

VIII POST-TESTS

The following are two sample Post-Tests to evaluate student performance on this module. Clearly, each is too long for a 50-minute exam period. Either the exam period must be lengthened or the number of questions requiring answers decreased. It is expected that about 5 questions would constitute an hour exam, so that several tests could be constructed from the following two tests.

Test A

1. If 5 cm^3 of oil has a mass of 4 grams, what is the density of the oil and its specific gravity?
2. A cylindrical water tower is constructed to withstand a maximum pressure of 200 PSI. If the water tower has a 20-foot diameter and is loaded with 6,000,000 lbs of water, will the maximum pressure limit be exceeded?
3. Write a simple statement of Pascal's Law. Describe a simple experiment to test Pascal's Law which would demonstrate your knowledge and understanding of the law.
4. Write the relationship between:
   Pressure ($\underline{P}$)
   Depth in a fluid ($\underline{h}$)
   Weight density of the fluid ($\underline{d}$)
   If the pressure at a depth of 50 ft. in a fluid is 60 lbs/in^2, what is the weight density of that fluid?
5. Define gauge pressure in a simple sentence or two. If you use a formula, then write what each symbol represents.

   An automobile tire is inflated to 28 PSI (gauge pressure). What is the absolute pressure in the tire?
6. Sketch a diagram of a mercury barometer. Label the diagram and describe the operation of the barometer.
7. A hydraulically operated metal-stamping press has a 1" diameter input cylinder and a 6" diameter output cylinder for compression.
   a) Calculate the ideal mechanical advantage of the press. Show all of your work including any formula used.
   b) If an input force to this press of 50 lbs results in an output force of 1500 lbs, calculate the actual mechanical advantage and the % efficiency of the press.
   c) If the output (stamping) piston travels 1/12 inch in an operation, how far does the input piston travel?
8. Given a hydraulic lift system, describe how to experimentally determine the ideal mechanical advantage, the actual mechanical advantage, and the efficiency of the system. Clearly state what <u>measurements</u> you would make, and in what calculations you would use those measured values.
9. Write Archimedes' Principle. Give an example which demonstrates your understanding of his Principle.
10. A blob of glop has a volume of 35 cm^3. The density of glop is 4 g/cm^3. What is the buoyant force on the blob when it is submerged in water?
11. A 6" diameter water main is opened to fill a swimming pool. The flow velocity is 30 inches/sec. How many cubic feet of water will flow in 24 hours?
12. Bernoulli's Equation:
    $\underline{P} + \rho \underline{gh} + 1/2\ (\rho \underline{v}^2) = \text{constant}.$
    At one point in a horizontal section of a liquid metal pumping system, mercury (density 13.6 g/cm^3) is pumped at a pressure of 4.40×10^6 $dynes/cm^2$ and a velocity of 300 cm/sec. Further along in the same assembly the tubing diameter is changed, causing the velocity to double. What value does the pressure now have?
13. A 165-foot-high dam springs a small leak at its base. Use Bernoulli's Equation to calculate the outflow velocity of water. If the hole has a cross-sectional area of 0.25 square inches, how much water leaks out in 12 hours? Bernoulli's Equation:
    $\underline{P} = \rho \underline{gh} + 1/2\ (\rho \underline{v}^2) = \text{constant}.$
14. In a 1" diameter garden hose the flow velocity is 3 ft/sec. At the nozzle the diameter is decreased to 1/16 inch. What is the velocity at the nozzle?

15. Define each of the following terms in a sentence or two. If you use an equation, state what each symbol represents.
 a) Pressure
 b) Displaced fluid
 c) Buoyant force
 d) Barometer
 e) Efficiency
 f) Bourdon gauge
 g) Venturi effect
 h) Pitot tube

Test B

1. A 6.25-pound cylinder of gold has a cross-sectional area of 1.25 in^2. What force and what pressure does it exert on the top of a glass tube if it is stood on end?
2. A drum has a volume of 6 cubic feet. Empty, the drum weighs 4 lbs. When filled with a chemical, the drum weighs 400 lbs. What is the density of the chemical?
3. Write a statement of Pascal's Law and describe a simple experiment which demonstrates your understanding of this law. Include a simple sketch (clearly labeled) of any apparatus.
4. The density of salt water is 64 lbs/ft^3. At what depth will a diver experience a pressure of 80 lbs/in^2?
5. A hydraulic elevator is operated from a pump which develops 60 lbs/in^2 pressure. The lift cylinder has an inside diameter of 7".
 a) What is the maximum lift force that the elevator can provide if there are no frictional losses?
 b) If the lift can only lift 1800 lbs, what is its efficiency?
6. An aluminum canoe weighs 80 lbs and displaces 20 cubic feet of water when submerged to the gunwales. Four campers (average weight 200 lbs) load 600 lbs. of gear into the canoe and then climb in themselves. Does the canoe sink?
7. A water tower contains a forty-four-foot depth of stored water to pressurize the fire sprinkler system of a factory. The factory's sprinklers are 20 ft below the bottom of the water tower. Calculate the outflow velocity at each sprinkler head when the sprinklers are first turned on. Bernoulli's Equation: $\underline{P} + \rho \underline{gh} + 1/2\ (\rho \underline{v}^2) =$ constant.
8. Define each of the following in a simple sentence or two. If you use an equation, state what each symbol represents.
 a) Pressure
 b) Venturi effect
 c) Efficiency
 d) Bourdon gauge
 e) Displaced fluid
 f) Pitot tube
9. A man weighing 140 lbs stands on a rigid steel plate which weighs 80 lbs. If the plate is 12 inches on a side, what pressure is exerted on the floor beneath the plate? What pressure is exerted if the plate is 24 inches on a side (and is still rigid and weighs 80 lbs)?
10. Define gauge pressure and absolute pressure and tell how to convert from one to the other. A man's blood pressure is recorded as 120/80. Is this gauge pressure or absolute pressure? Convert these to $pounds/in^2$.
11. An 18" diameter water main must supply 1" diameter feeder lines at 20 PSI. Each feeder can deliver 37.5 gallons/minute. What pressure in the main will supply the flow to one feeder? Bernoulli's Equation: $\underline{P} + \rho \underline{gh} + 1/2\ (\rho \underline{v}^2) =$ constant.
12. A drip in a sink faucet loses a cubic foot of water a day. If the water pressure is 20 lbs/in^2,

what is the effective area of the leak in square inches? Bernoulli's Equation: $\underline{P} + \rho g \underline{h} + 1/2\ (\rho \underline{v}^2)$ = constant.

13. Water from a fire hose is squirted to a height of 60 feet. If after an hour the pressure has dropped to half the initial value, how high does the water now go? Compare the outflow velocity for the two cases.

14. A pitot tube is used to measure the flow velocity in a chemical processing plant. The static pressure reads 16 PSI when the impact pressure reads 24 PSI. If the density of the chemical is 128 lbs/ft^3, what is the flow velocity?

15. A two-piston hydraulic system has an ideal mechanical advantage of 60 and an efficiency of 80%. What is the large piston's diameter if the small piston has 1/2 inch diameter? If the input force is 200 lbs, what is the output force?

VIII ANSWERS TO POST-TESTS

Test A

1. $\rho = .8\ g/cm^3$; S.G. = .8
2. No, $\underline{P}$ = 133 PSI
3. Refer to section on "Closed Systems".
4. $\underline{P} = \underline{hD}$; $\underline{D} = 0.1\ lb/in^3 = 173\ lbs/ft^3$
5. $\underline{P}_{ABS}$ = 42.7 PSI
6. Refer to section on "Atmospheric Pressure".
7. a) IMA = 36
   b) AMA = 30; EFF = 83%
   c) 3 inches
10. 34,300 dynes
11. 42,400 ft^3/day
12. $2.56 \times 10^6\ dynes/cm^2$
13. $\underline{v}$ = 103 ft/sec; $\underline{V} = 7700\ ft^3$
14. $\underline{v}$ = 64 ft/sec
15. Refer to appropriate section of the module.

Test B

1. $\underline{F}$ = 6.25 lbs; $\underline{P} = 5\ lbs/in^2$
2. $\underline{D} = 66\ lbs/ft^3$
3. Refer to section on "Closed Systems".
4. $\underline{h}$ = 180 ft
5. a) $\underline{F}$ = 2310 lbs
   b) 78%
6. Yes, overload of 230 lbs
7. $\underline{v}$ = 64 ft/sec
8. Refer to appropriate section of the module.
9. a) 220 lbs/ft^2
   b) 55 lbs/ft^2
10. $120/80 = \dfrac{2.32}{1.55}$
11. 21.6 PSI
12. $3.07 \times 10^{-5} in^2$
13. a) 30 ft; $\underline{V}_1/\underline{V}_2 = \sqrt{2}$
14. 4.2 ft/sec
15. $\underline{D}_2$ = 3.87 inches; $\underline{F}$ = 9600 lbs

IX LIST OF APPARATUS

Experiment A-1

1. Auto jack 1 1/2 ton. Can be purchased at any auto supply store. There are some recommended modifications:
   a) Drill holes in the base and screw to a base plate about 12" x 12" or larger (aluminum recommended) to add stability and reduce chances of accident. See Figure 1.
   b) Load the plate to distribute the force of the jack on the student's foot. Note that it can be made from a 6" long piece of 2" x 4" wood. Drill a hole approximately in the center to fit the piston of the jack.
2. Pull balance 0-5 pounds.
3. Variety of devices: aspirator, siphon, gauges, barometer, etc.
4. Two-cylinder demonstration system with auto-brake light switch and oil pressure light switch.

Schematic diagram is shown in Figure 2.

Experiment A-2

1. Selection of hydrometers.
2. Automotive antifreeze hydrometer, floating ball type.
3. Variety of fluids, many of which can be purchased in a supermarket.
4. Ethylene Glycol antifreeze. (Pick a brand with a label on the container or refer to Handbook of Physics and Chemistry for table of mixture vs. temperature.)
5. Hydrometer jars or other suitable containers.

Experiment B-1

1. Water stand-pipe column--copper approximately 1 ½" diameter x 4 ft long, fitted with about four Tee fittings and an end cap for the bottom end. A sketch of a port is shown in the module. The ports can be sealed with any thin rubber or plastic sheet. Plastic garbage bags, balloons, and other common sources are sufficient. Rubber bands provide adequate sealing tension.
2. Push balance (0-1000 grams). Source: Chattilon Scale Co., Long Island City, NY.
3. Metal disk pusher plates. Two-cm diameter with a blind hole drilled part way through to accept the push rod of the balance.

Experiment B-2

1. Balance 0-500 grams, with hook below pan for suspension of objects.
2. Beakers.
3. Assorted cylinders, irregular objects, wood blocks, and a sinker.
4. Graduated cylinders 0-125 cc.

Experiment B-3

1. Two glass hypodermic syringes of different diameters. Suggestion: 10 cc and 30 cc ground glass. (Plastic syringes have too much friction.)
2. Rubber or plastic tubing.
3. Push balance 0-2000 grams. Supplier: Chattilon Scales Co., Long Island City, NY.
4. Oil or water hydraulic fluid.
5. Slotted weights.
6. Two low-friction pulleys.

Schematic diagram is shown in Figure 3.

Experiment C-1

See Student Module

Experiment C-2

Standard sphygmomanometer and stethoscope. See, for example, Edmund Scientific Co., Barrington, NJ.

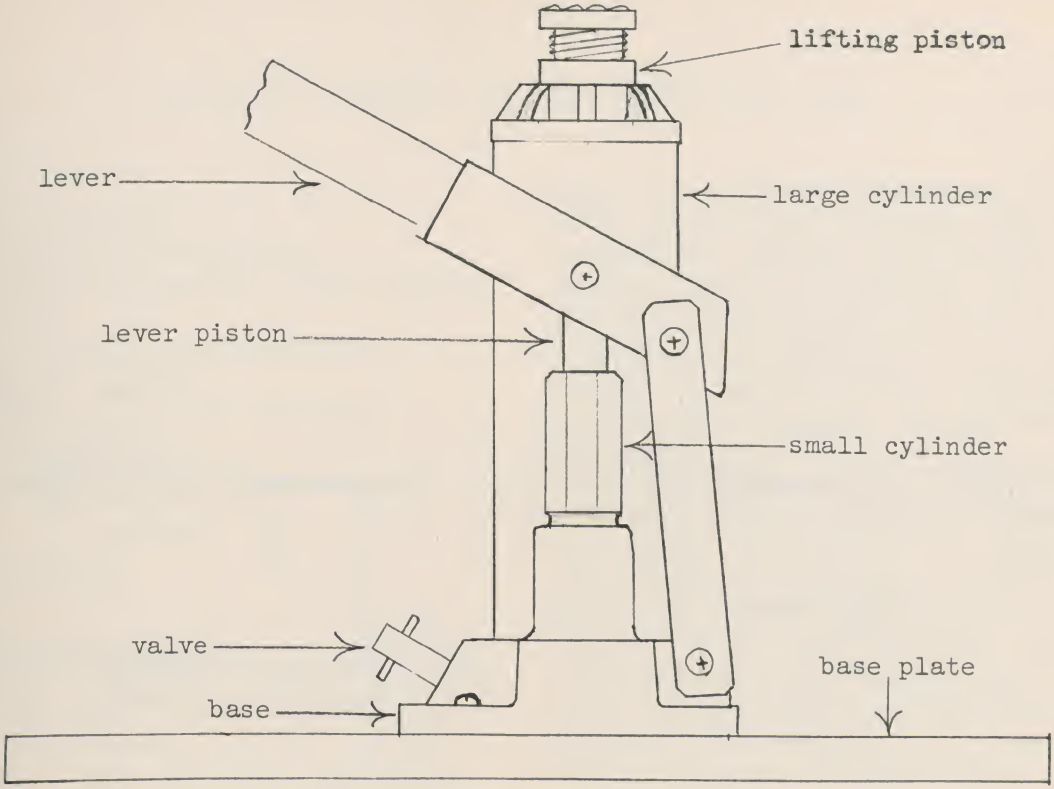


Figure 1.

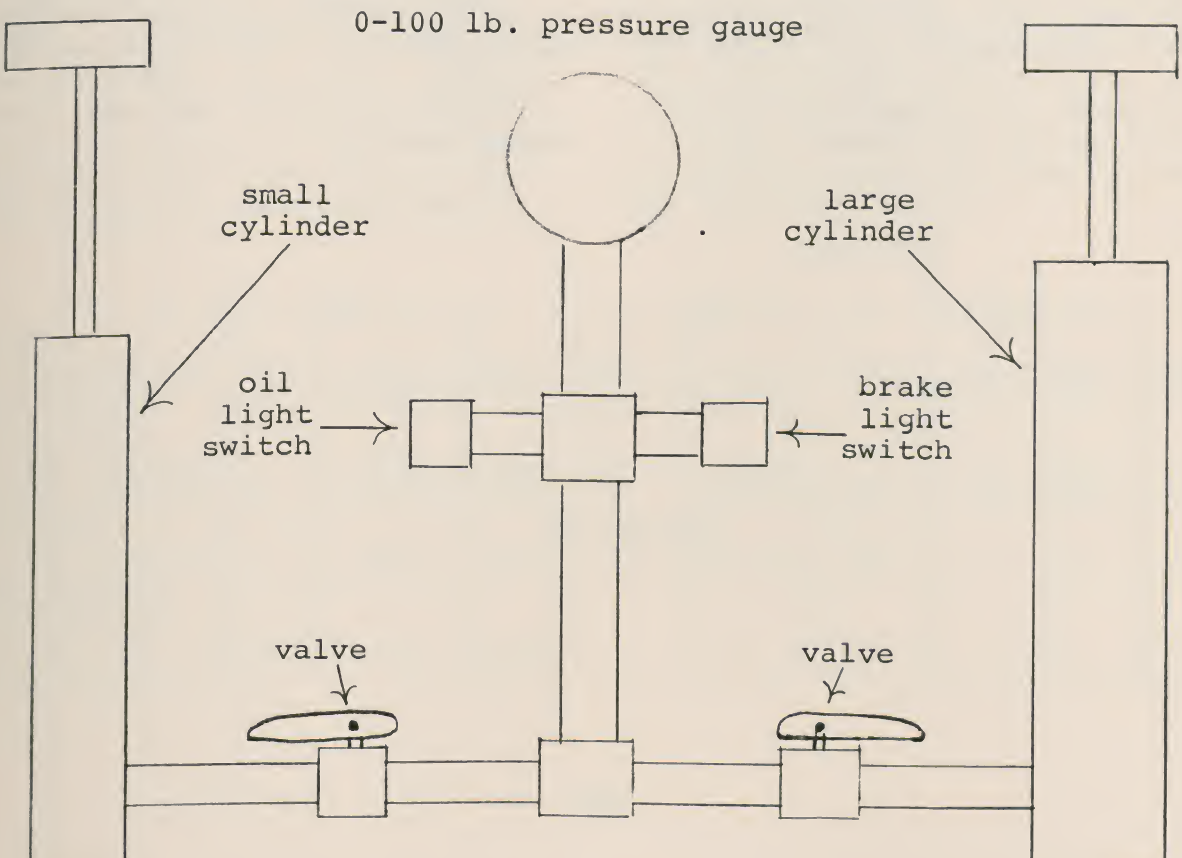


Figure 2.

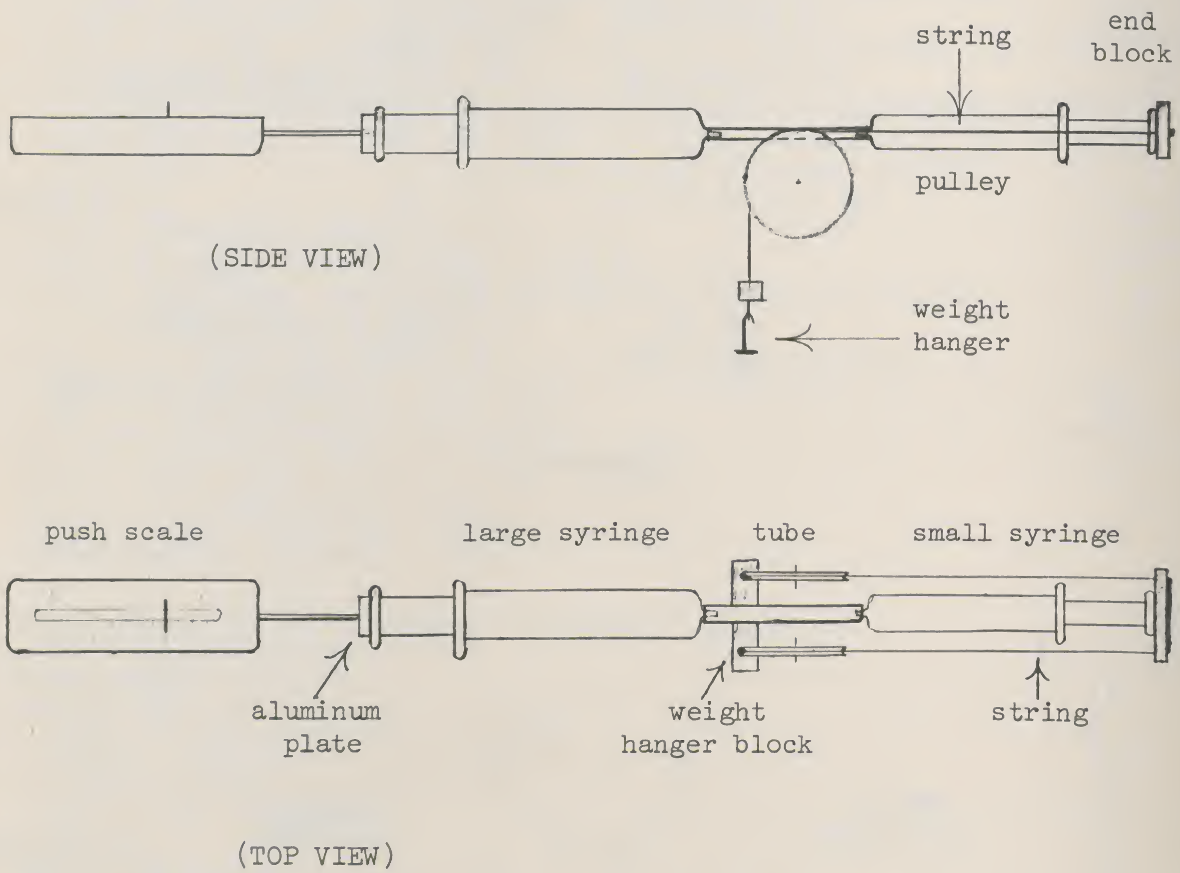

string
end block
pulley
(SIDE VIEW)
weight hanger
push scale
large syringe
tube
small syringe
aluminum plate
weight hanger block
string
(TOP VIEW)

Figure 3.

INSTRUCTOR'S MANUAL FOR THE INCANDESCENT LAMP

CONTENTS

I INTRODUCTION

The Incandescent Lamp module covers the physics concepts, definitions, and principles which can be derived from a radiating source, such as the incandescent lamp, the power and spectral properties of a radiating source, the response of the eye to radiation, and the illumination of various surfaces. The module emphasizes the following concepts and principles: the continuous spectrum emission from a high temperature material; the dependence of pressure of a gas on absolute temperature; the dependence of electrical resistance on temperature; the dependence of radiant power on absolute temperature (Stefan-Boltzmann Law); the shift of wavelength for peak power output with changing absolute temperature (Wien's Displacement Law); the dependence of luminous flux on wavelength, response of the eye, temperature, and geometry of the radiating surface; and the inverse variation of surface illumination with distance from the source.

The incandescent lamp (light bulb) is examined from its physical characteristics (shape and kind of filament and environment, electrical properties, power losses and efficiency) to the nature of the radiated power (spectral, eye response, and illuminating properties). These optical principles and concepts are related to the manufacturer's ratings of input power and luminous output.

The incandescent lamp module is divided into three separate sections. Each section is intended to form one week of instruction, and the module can be used for one week, two weeks, or three weeks depending upon the needs and capabilities of your class.

Although this module was designed for three weeks of instruction, there are several alternative ways in which the module can be used.

	Week 1			Week 2			Week 3		
Student Characteristics	Sec.	Lab	Demo	Sec.	Lab	Demo	Sec.	Lab	Demo
High Ability	B	B-1,2,3	-	C-1	C-1	-	-	-	-
Better than Average Ability	B	B-2	B-1	B,C	B-3	-	C	C-1	-
Average Ability	A	A-1	A-2	B	B-2,3	B-1	C	C-1	-
Less than Average Ability	A	A-1	A-2	B	B-2,3	B-1	-	-	-
Class with no math prerequisites	A	A-1	A-2	-	-	-	-	-	-

The first section is largely qualitative. The student is introduced to the emission of light from a heated object in the lab, and he makes several observations which raise questions about physics, but for which answers are not yet provided. The first section is concluded with a discussion of the spectral properties of incandescent metals which explain some of the students' observations and a summary of the qualitative principles and concepts he has learned. Two post-tests based on the goals of Section A of the module are included in Section 8 of the Teacher's Guide.

The second section of the module has the student arrive empirically (in the lab) at the concept of absolute temperature and absolute zero, and the dependence of pressure of a gas, electrical resistance of a tungsten filament, and the radiated power from a tungsten filament on the absolute temperature. The empirical equations are discussed quantitatively with appropriate problems and exercises. The section is concluded with a summary of principles and concepts the student has learned and then with applications of these principles to other devices.

Section B has its own goals and post-tests which measure achievement of these goals.

Section C is a theoretical and analytical section. It derives luminous efficacy in terms of eye response, wavelength, spectral exitance, surface area, and temperature. The student performs a laboratory verification of the temperature dependence of luminous efficacy. The section is concluded with a derivation of illuminance and a discussion of recommended illuminance for various visual tasks, and then a summary of the principles and concepts learned in Section C. This section also has its own goals and post-tests.

II SPECIAL PREREQUISITES

The module presents most of the optical principles necessary for an understanding of the incandescent lamp. However, the only electrical property discussed is the variation of electrical resistance with temperature. Other electrical principles of the incandescent lamp may be considered as prerequisites to the module. The principles and skills needed include a working knowledge of Ohm's Law and D.C. circuit power equations, as well as the ability to read meters and make simple circuit connections.

A recent course in high school algebra is sufficient as a math prerequisite for this module. A course in college algebra is more than sufficient.

III TABLE OF CONTENTS OF THE MODULE

Temperature Coefficient of Resistance
Relative Resistance of Tungsten
Radiant Power and Temperature
Experiment B-3. Relationship of Radiated Power to Temperature
Method I. Trial and Error
Method II. Log-Log Plotting
Blackbodies and Graybodies
Radiant Exitance
The Stefan-Boltzmann Law
Summary
Other Applications of the Principles
Goals for Section C
Section C. An Analytical Approach
Spectral Radiant Exitance
Wein's Displacement Law
Luminous Flux
Luminous Flux from Source with Extended Wavelength Range
Luminous Efficacy
Luminous Flux from a Graybody
Filament Temperatures
Overall Luminous Efficacy
Illuminance
Inverse Square Law
Experiment C-1. Luminous Efficacy of a Tungsten Filament
Numerical Values for Illuminance
Summary
Worksheets
Glossary

IV GOALS

The objectives of the <u>Incandescent Lamp</u> module have been included at the beginning of each section of the module. Each objective has been stated in general terms using common words, rather than the detailed, technical language of a behavioral objective. These statements are then called goals, rather than objectives. To meet the criteria one normally expects of objectives, a sample item has been included with each goal. When a student can demonstrate to himself that he can respond correctly to any item like the one given, he knows that he has met that objective.

Section 8 of this Teacher's Guide contains tests which measure the achievement of samples of the goals from each section. These tests can be used to evaluate student performance weekly, or at the end of two weeks, or at the conclusion of their study of the entire module. A statement of these goals follows:

1. Know what the terms continuous spectrum and line spectrum mean, and when to expect each.
2. Know which colors are spectral colors and their relative positions in the spectrum.
3. Know the definition of wavelength.
4. Understand the relation between the temperature of a hot object and its color.
5. Be able to use a simple calibrated spectrometer to measure wavelength.
6. Understand the absolute temperature scale and its relation to the pressure of an ideal gas at constant volume.
7. Know how the electrical resistance of a conductor varies with temperature.
8. Understand the definitions of blackbodies and graybodies.
9. Know the definitions of absorptance, emissivity, irradiance, and radiant exitance.
10. Understand the Stefan-Boltzmann Law.
11. Know the definition of spectral radiant exitance.
12. Know the relation of the total radiant exitance of a graybody to the graph of spectral radiant exitance versus wavelength.
13. Understand Wien's Displacement Law, and its relation to the Stefan-Boltzmann Law.
14. Understand the concept and graph of relative luminosity.
15. Know the definition of luminous flux and lumens.
16. Understand the concept of luminous efficacy and the graph of this quantity versus temperature for a graybody.

17. Know the definition of illuminance.
18. Know the illuminance as a function of distance from a point source emitting uniformly in all directions.

V DISCUSSION OF ACTIVITIES

a. Laboratory Activities

Experiment A-1. Emission of Light and Heat by Solids

The purposes of this experiment are: to demonstrate to the student that metal objects heated to relatively high temperatures emit light (and heat) depending on how high their temperature is, and that the colors go from red to yellow to white as the temperature is increased.

The apparatus needed for one set-up of Experiment A-1 is as follows:

Item	Quantities
Bunsen burner	1
Lab stand with clamp	1
Iron wire	1
Copper wire	1
Color comparator	1
Clear, long filament, incandescent lamp	1
Lamp socket	1
D.C. Power Supply (0-100 volts, 0-0.5 A)	1
D.C. Ammeter (0-0.5 A)	1
D.C. Voltmeter (0-100 V)	1
Ring stand	1

Experiment A-2. Analysis of White Light

The purposes of this experiment are to have the student observe that white light is made up of the spectral colors and that the spectrum may be produced by means of a prism or diffraction grating. The student observes the relative intensity of the light from an incandescent lamp in different portions of the spectrum as the voltage to the lamp is varied.

The apparatus needed for one set-up of Experiment A-2 is as follows:

Item	Quantities
Optical bench	1
Component holder for optical bench	3
Collimated light source	1
Single slit	1
Component table	1
Prism	2
Diffraction grating	1
White screen	1
Spectrometer (hand held)	1
Long filament, clear, incandescent lamp	1
Mercury vapor lamp	1
Fluorescent lamp	1
D.C. Power Supply (0-100 V)	1

Experiment B-1. Determining the Value of Absolute Zero

The purpose of this experiment is to obtain a pressure versus Celsius temperature curve for a constant volume air thermometer and then to extrapolate that curve to zero pressure to find an approximate value for absolute zero of temperature.

The apparatus needed for one set-up of Experiment B-1 is as follows:

Item	Quantities
Constant volume thermometer	1
Mercury thermometer	1
Large beaker	1
Bunsen burner	1
Ring stand	1

Experiment B-2. The Relationship of Resistance to Temperature for a Conductor

The purpose of this experiment is to measure the resistance of an incandescent lamp filament at various temperatures and then determine the near

linear relationship between resistance and temperature.

The apparatus needed for one set-up of Experiment B-2 is as follows:

Item	Quantities
Incandescent lamp filament and base	1
Lamp socket	1
Ring stand	1
Beaker	1
Bunsen burner	1
Ohmmeter	1
Mercury thermometer	1

Experiment B-2. Relationship of Radiated Power to Temperature

The purpose of this experiment is to obtain the Stefan-Boltzmann Law for radiated power from an incandescent lamp. The student measures the input voltage and resulting current in an incandescent lamp. From these values he then computes the input power and the resistance of the filament. From a graph of the relationship of resistance to temperature for tungsten the student obtains the temperature for each power setting of the lamp. Two methods of determining the relationship are discussed including the semi-log plot method.

The apparatus needed for one set-up of Experiment B-3 is the same as that for Experiment A-1.

Experiment C-1. Luminous Efficacy of a Tungsten Filament

The purpose of this experiment is to measure the luminous flux from an incandescent lamp by means of a Bunsen photometer and from the input power to calculate the luminous efficacy for the lamp. The variation of luminous efficacy with temperature is studied by means of a plot of these two quantities.

The apparatus needed for one set-up of Experiment C-1 is as follows:

Item	Quantities
25 watt lamp	1
Lamp socket	2
Standard lamp	1
Optical bench	1
Component holder for optical bench	3
Bunsen photometer	1
D.C. Power Supply (0-200 V)	1
D.C. Ammeter (0-1 A)	1
D.C. Voltmeter (0-200 V)	1

b. Other Activities

The Incandescent Lamp module has been designed for use in an introductory physics course which has two or three hours of laboratory time per week and three fifty-minute classes per week. This module is most appropriate in the second semester physics course. The subject matter, current electricity and photometry, is typically treated in the second semester. However, the module may be used at any point in a course, but should be used after the prerequisites listed in the module or in Section II of this Teacher's Guide have been met.

Physics of Technology modules can be used most effectively if you avoid lectures entirely. Class time can be most interesting and helpful to students if you will spend that time doing demonstrations, discussing the laboratory work, and asking students about questions and problems in the module. A list of resource material is included at the end of this section.

c. Resource Material

A. 16-mm Sound Film

1. "Sight, Light and Color"; General Electric Educational Film, Scotia, New York 12302.

2. "The Light in Your Life", G.E.
3. "Heat as Radiant Energy"; Cenco Educational Film, Chicago, Ill. 60623.
4. "Light: Illumination and its Measurement"; Coronet Instructional Films.
5. "Radiation of Heat"; MGHT, McGraw Hill.
6. "Light Sources and Their Spectra"; Encyclopedia Britannica Film.
7. "Color Quality of Light in Photography"; Thorne.

B. <u>8-mm Film Loops</u>
1. "Light-Shadows", Rank, Overseas Film Distribution.
2. "Finding Absolute Zero", The Ealing Corporation.
3. "Heat Distribution in the Spectrum", Film Associates.

C. <u>Transparencies</u>
1. Constant Volume Gas Thermometer, HS8, Ed. Service, John Wiley & Sons.
2. "Color Refraction", No. F6767, Frey Scientific Co.
3. "Color Dispersion Using Two Prisms", No. F-6768, Frey.

VI SAMPLE DATA

Experiment A-1. Part I

1. Yes. The tip of the wire emits light.
2. Red. The tip is almost yellow and color goes toward red down the wire.
3. Name (second red from end).
4. Wire tip is a little brighter.
5. Seems to be more yellow.
6. Between (second and third from end).
7. Red becomes darker and then to no light emitted at all.
8. Same as iron wire.
9. Name (second from red end).
10. No.
11. Same as in 6.
12. 1100°C.
13. Hot metals emit light; doesn't depend on temperature. Light goes from red to yellow.

Experiment A-1. Part II

1.	10 V	0.06 A	Color not visible.
	20 V	0.1 A	Color not able to match.
	30 V	0.13 A	Color 2nd from red end.
	40 V	0.15 A	Color 3rd from red end.
	50 V	0.17 A	Color 4th from red end.
	60 V	0.19 A	Color 4th from red end.
	70 V	0.21 A	Color 4th from red end.
	80 V	0.23 A	Color 5th from red end.
	90 V	0.24 A	Color 6th from red end.
	100 V	0.26 A	Color 7th from red end.

2. White.
3. Yes. Because the copper wire was at 1100°C and only dull red.
4. Yes. Nearly because current changed some for each 10 V.
5. Feel heat and the heat decreases as the voltage is lowered.

Experiment A-1. Part III

1. Yes. A dull red glow in a darkened room.
2. Yes, it emits heat.
3. Hot objects emit both light and heat. As the object gets hotter more heat is emitted and the light goes from red to yellow to white.

Experiment A-2. Part I

1. Violet, blue, green, yellow, and red.
2. No.
3. From the white light.
4. No.

5. Yes, the colors were in the light because if the first prism added color the second should have added more.
6. Yes.
7. Same as the colors with the prism.
8. Same band of colors except that red and blue end are interchanged.

Experiment A-2. Part II

1. Same spectrum as in Part I.
2. Violet, blue, green, and yellow-orange lines. Not a continuous spectrum as with incandescent lamp.
3. The same spectrum as with incandescent lamp is visible with the mercury lines superimposed.

Experiment A-2. Part III

1. No. Yellow is much brighter.
2. Brightness decreases as voltage decreases.
3. Red and green are very bright. The rest is not visible.
4. When the lamp glows red all the light is red. When it glows white it contains all the colors.
5. As temperature gets hotter color goes from red to orange to yellow to white.

Experiment B-1.

1. 15.25 $26^{o}C$.
2. 13.9 $0^{o}C$.
3. 19.2 $100^{o}C$.
4. See graph on page 178.
5. Absolute zero = $-265^{o}C$.

Experiment B-2.

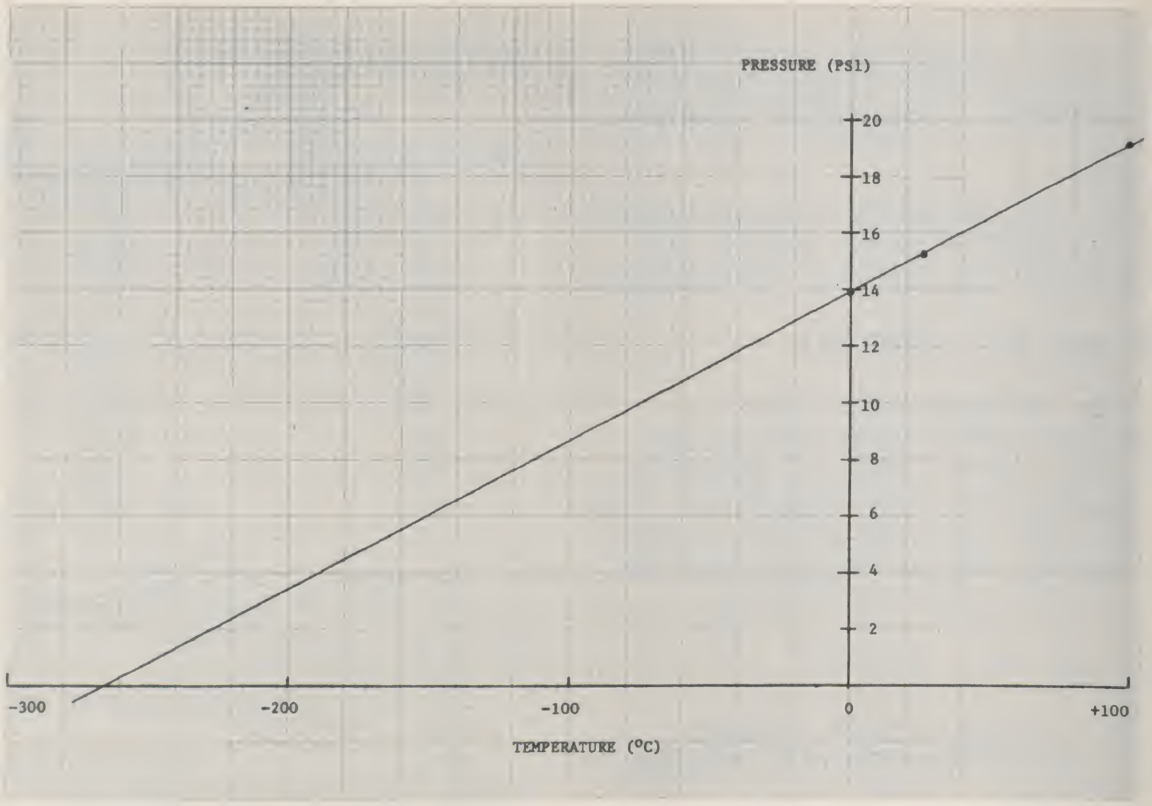
WORK SHEET

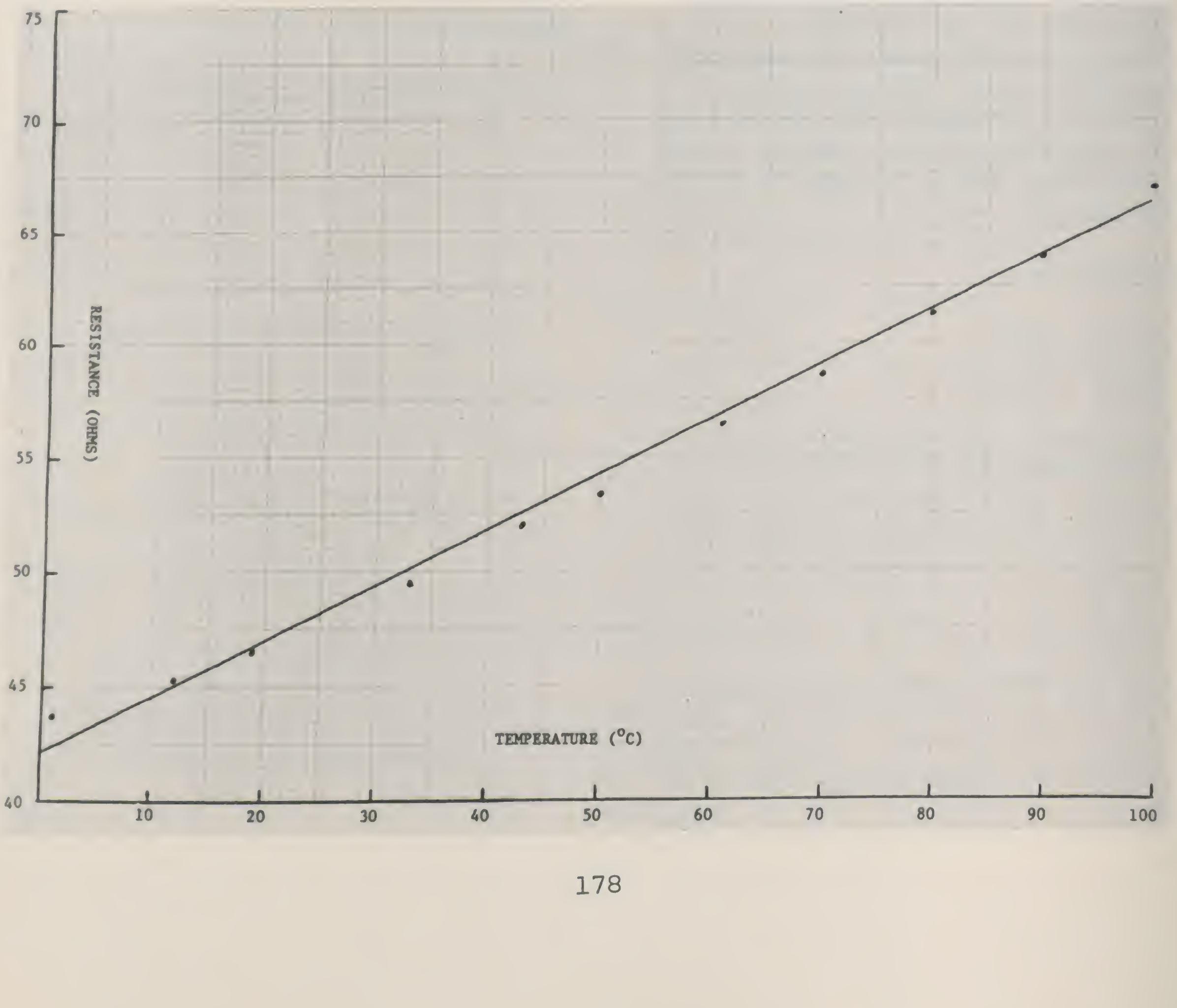
Temperature (^{o}C)	Resistance (Ohms)
1	43.7
12	45.3
19	46.5
33	49.5
43	52.0
50	53.3
61	56.4
70	58.6
80	61.3
90	63.8
100	67.0

2. See graph on page 178.
3. The line is almost straight.
4. Slope = $0.24\ \Omega/^{o}C$.
5. Intercept = $42.2\ \Omega$.
6. Temperature Coefficient of resistance = 57×10^{-3}.
7. $1/^{o}C$.
8. $\underline{R} = 42.2\ \Omega + 0.24\ \Omega/^{o}C\ \underline{T_C}$.

Experiment B-3.

1. $\underline{R_o} = 39.1\ \Omega$.


PRESSURE (PS1)
20
18
16
14
12
10
8
6
4
2
-300
-200
-100
0
+100
TEMPERATURE (°C)


75
70
65
60
55
50
45
40
RESISTANCE (OHMS)
TEMPERATURE (°C)
10
20
30
40
50
60
70
80
90
100

2.

Power ($\underline{IV}$)	Resistance ($\underline{V}/\underline{I}$)	Relative Resistance ($\underline{R}/\underline{R}_o$)	Temperature (Kelvin)
3.48 watts	348 Ω	8.9	1650 K
5.68	394	10.1	1830
8.50	434	11.1	1985
12.54	490	12.5	2190
17.06	526	13.5	2345
22.86	572	14.6	2500
29.30	605	15.5	2640
36.86	640	16.4	2780

3. See graph on page 180. The graph is not a straight line.

4. Method I

Power	T_K^2	T_K^3	T_K^4	T_K^5
3.48 watts	2.72×10^6	4.94×10^9	7.41×10^{12}	1.22×10^{16}
5.68	3.35×10^6	6.13×10^9	1.12×10^{13}	2.05×10^{16}
8.50	3.94×10^6	7.82×10^9	1.55×10^{13}	3.08×10^{16}
12.54	4.80×10^6	1.05×10^{10}	2.30×10^{13}	5.04×10^{16}
17.06	5.50×10^6	1.29×10^{10}	3.02×10^{13}	7.09×10^{16}
22.86	6.25×10^6	1.56×10^{10}	3.91×10^{13}	9.77×10^{16}
29.30	6.97×10^6	1.84×10^{10}	4.86×10^{13}	1.28×10^{17}
36.86	7.73×10^6	2.15×10^{10}	5.97×10^{13}	1.66×10^{17}

5. See graphs on pages 180 and 181. $\underline{P}$ and $\underline{T_K}^4$ is nearly linear. $\underline{n} = 4$.
6. $\underline{P} = 6 \times 10^{-13}$ watts/K $\underline{T_K}^4$.

Method II

1. See graph on page 182.
2. Slope = 4.4 ≃ 4.
3. $\underline{P} = \underline{mT_K}^4$

Experiment C-1.

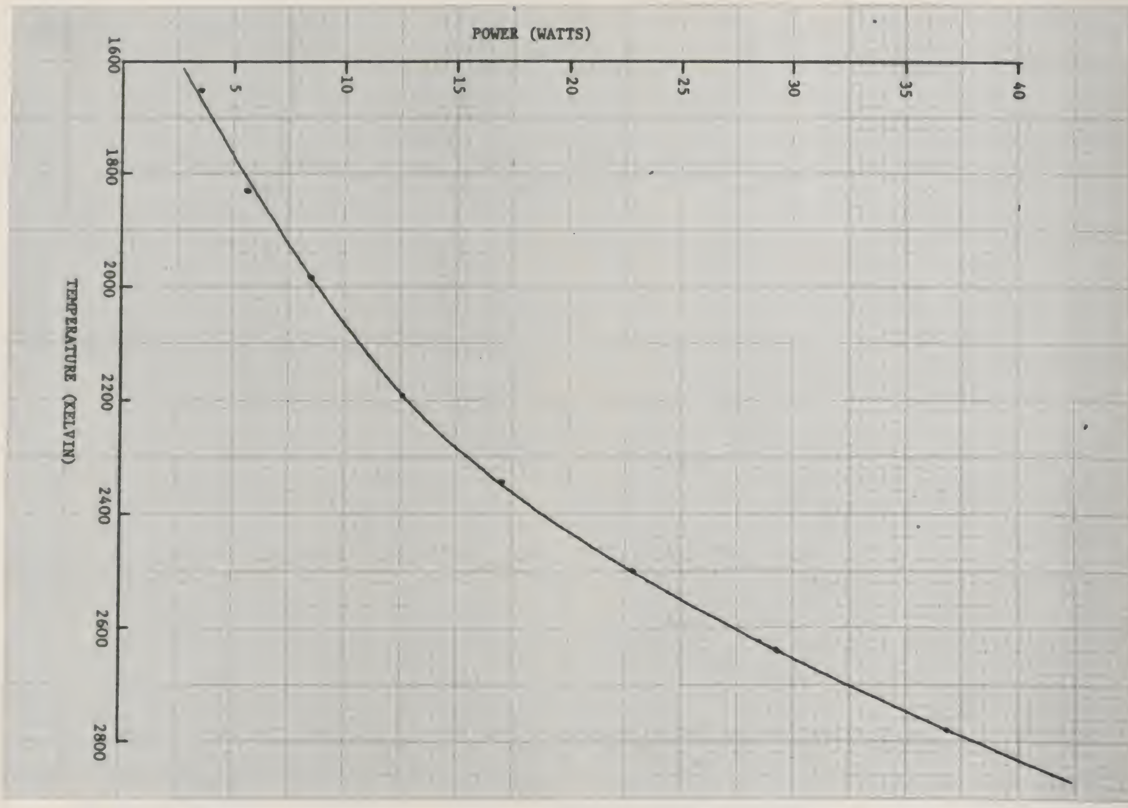
1. $\underline{F}_s$ = 471 lumens.
2. $\underline{V}$ = 65.0 volts, $\underline{I}$ = 0.14 A. $\underline{r}_s$ = 95 cm, $\underline{r}_x$ = 20 cm.

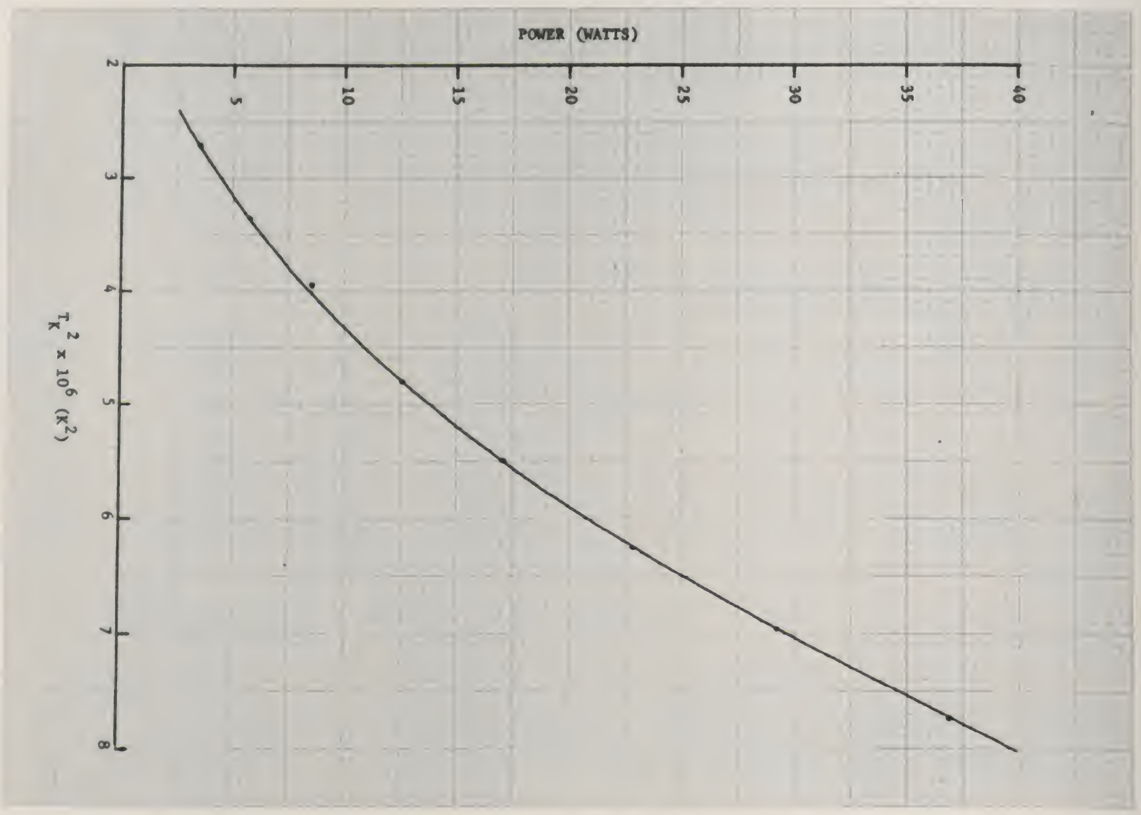
3.

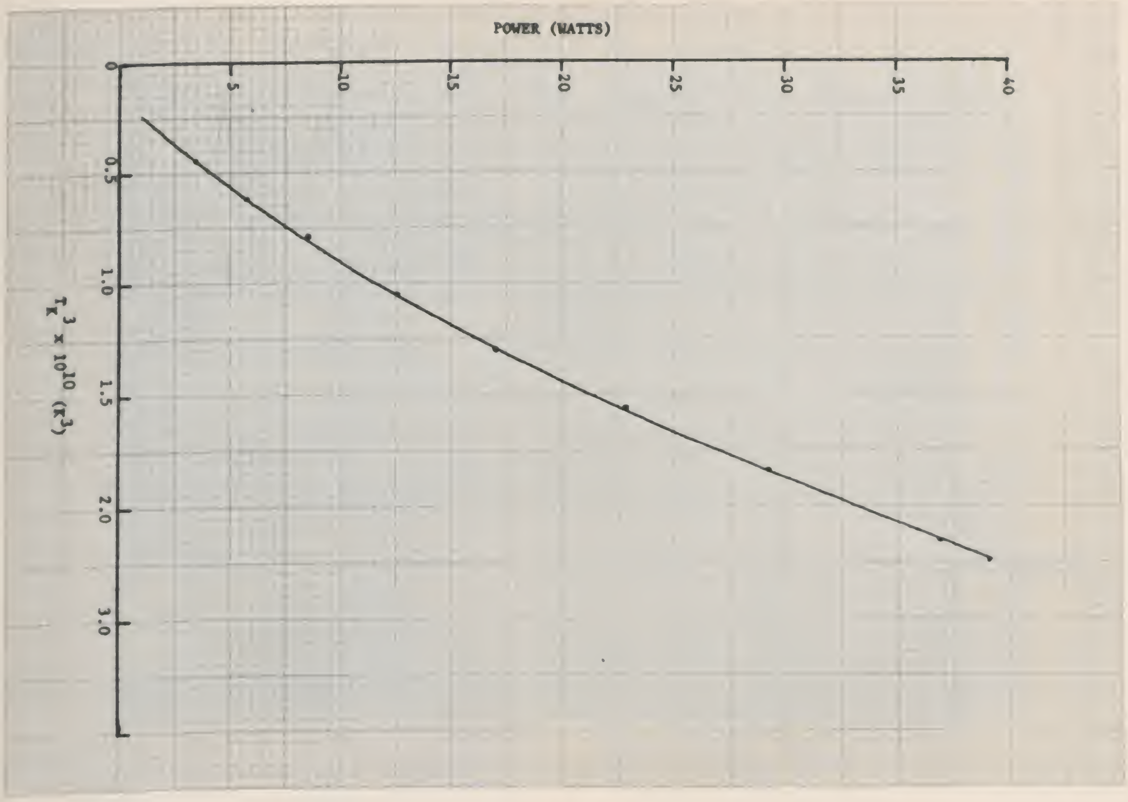
$\underline{V}$(V)	$\underline{I}$(A)	$\underline{r}_s$(cm)	$\underline{r}_x$(cm)
65.0	0.14	95	20
82.2	0.16	87	28
101.4	0.18	77	38
121.6	0.20	68	47
144.0	0.22	60	55
168.5	0.24	52	63

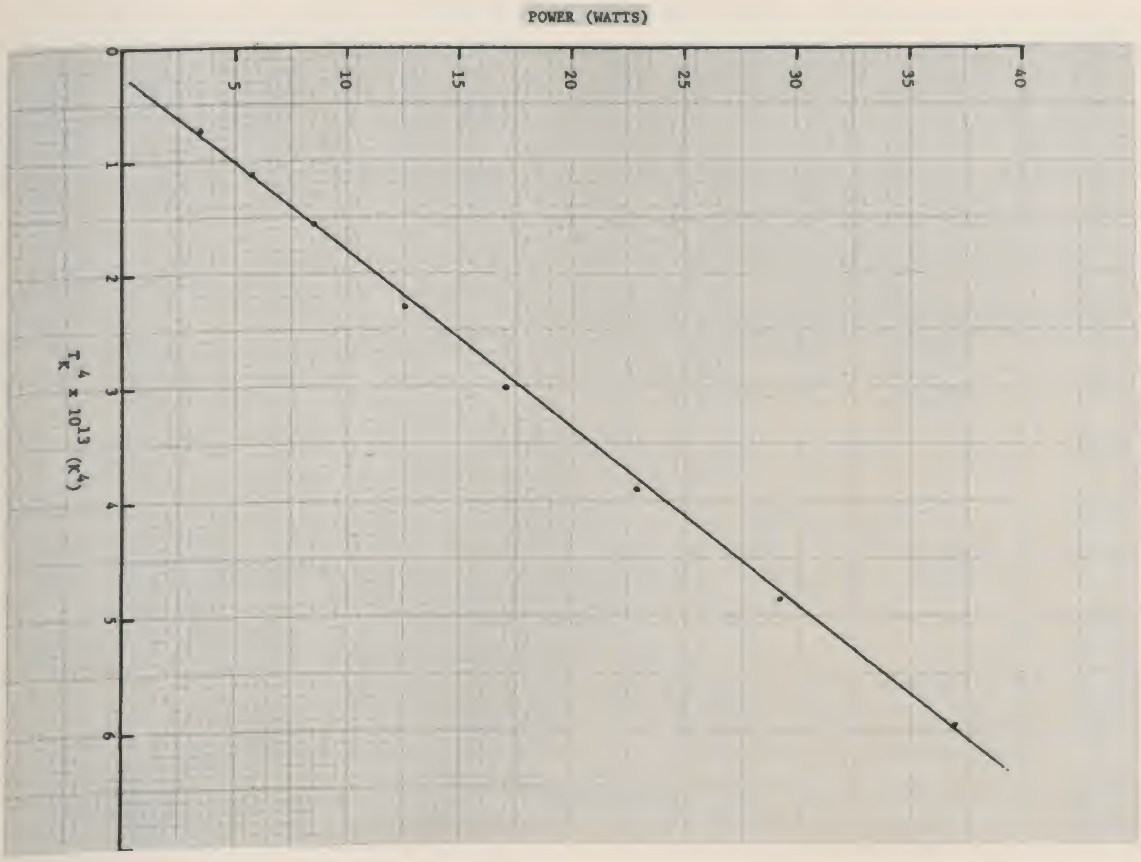
4.

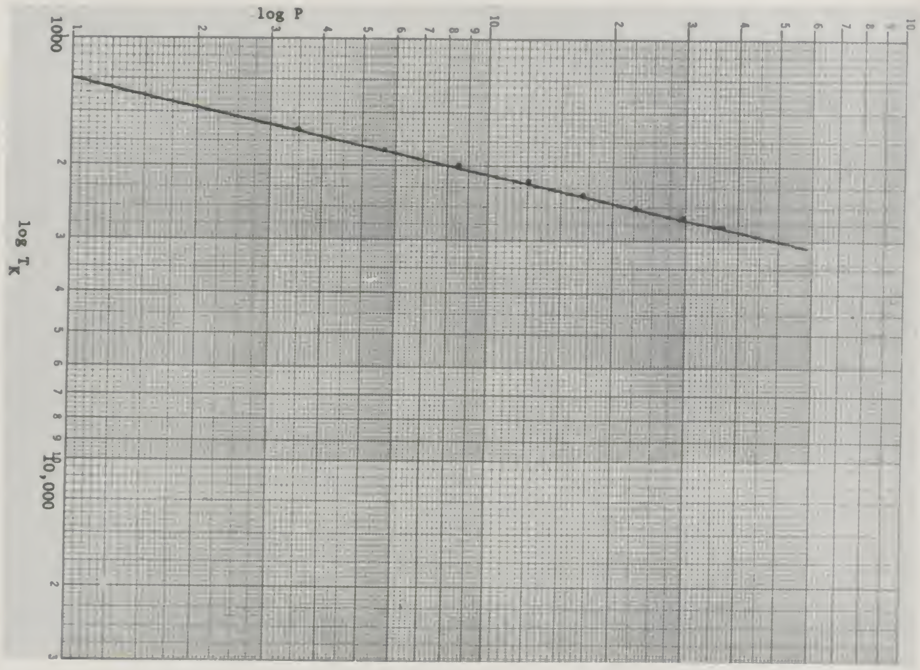
Trial	Power (watts)
1	9.10
2	13.15
3	18.25
4	24.32
5	31.68
6	40.44

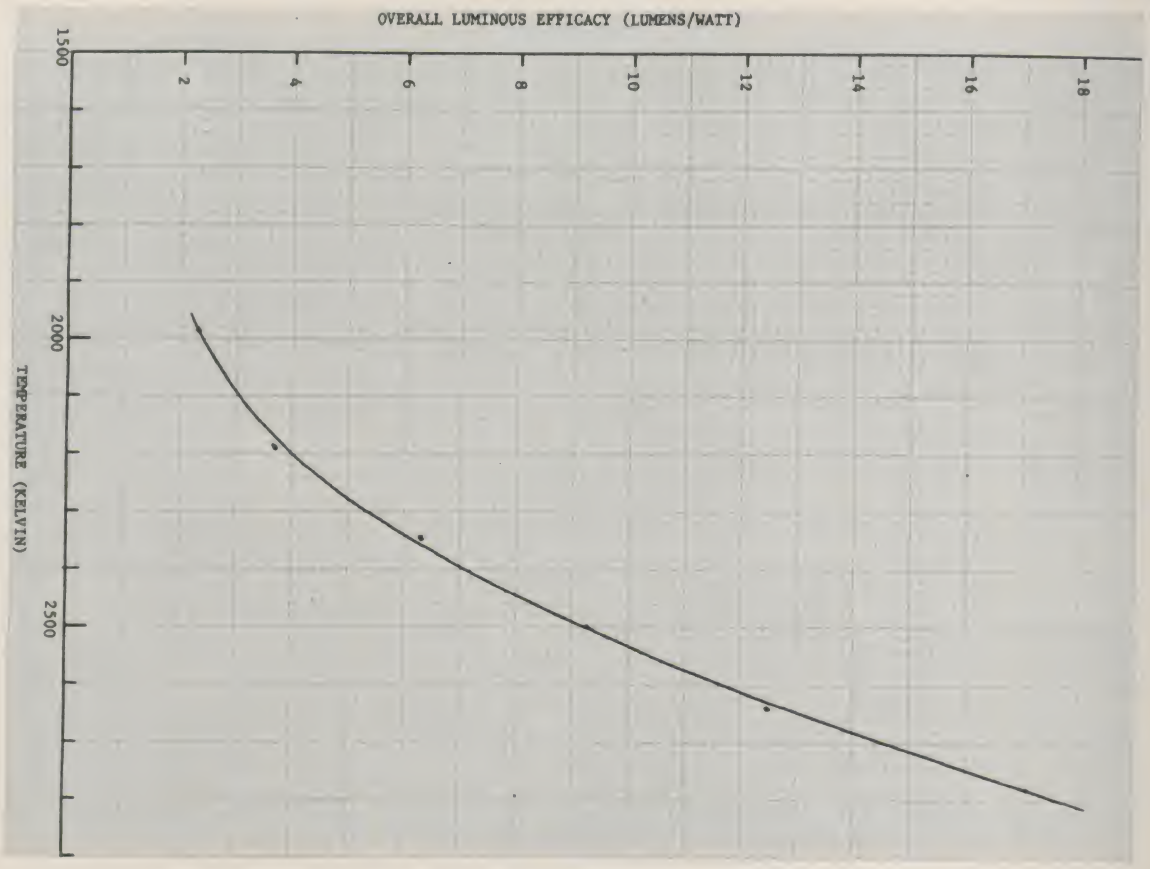

POWER (WATTS)
5
10
15
20
25
30
35
40
TEMPERATURE (KELVIN)
1600
1800
2000
2200
2400
2600
2800


POWER (WATTS)
5
10
15
20
25
30
35
40
$T_K^2 \times 10^6$ (K^2)
2
3
4
5
6
7
8


POWER (WATTS)
0
5
10
15
20
25
30
35
40
0.5
1.0
1.5
2.0
3.0
$T_K^3 \times 10^{10}$ (K^3)


POWER (WATTS)
0
5
10
15
20
25
30
35
40
1
2
3
4
5
6
$T_K^4 \times 10^{13}$ (K^4)


log P
log T_K
1000
10,000


OVERALL LUMINOUS EFFICACY (LUMENS/WATT)
TEMPERATURE (KELVIN)
1500
2000
2500

5.

Trial	F_x (lumens)
1	20.88
2	48.79
3	114.71
4	225.01
5	395.77
6	691.35

6.

Trial	e_o (lumens/watt)
1	2.29
2	3.71
3	6.29
4	9.25
5	12.49
6	17.10

7.

Current (A)	Temperature (K)
0.14	1985
0.16	2190
0.18	2345
0.20	2500
0.22	2640
0.24	2780

8. See graph on page 182. Graph has the same slope for the temperature range used, but the values are low.

VII SOLUTIONS TO PROBLEMS

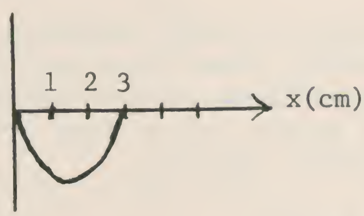
The problems and questions are an important part of the module. Questions should be discussed in class, in so far as possible. Many of the problems should be discussed in class, but if answers are provided, many students will work the problems outside of class and check their own work. The problem answers below are provided so that you can copy them and distribute them to students, if you wish.

1. 35 lb/in^2.
2. -191^oC.
3. 0.14 Ohms.
4. $3.7 \times 10^{-3}/C^o$.
5. 1600 K.
6. 2000 K.
7. ∿19.
8. 5.7×10^3 W/m^2.
9. 1.4×10^6 W/m^2.
10. 612,100 W/m^2.
11. -
12. -
13. 1.16×10^3 nm, infrared.
14. 1.18×10^3 nm.
15. $\sim 10^4$ nm, infrared.
16. 26,180 lumens.
17. 73,440 lumens.
18. 63.5 lumens.
19. 446,080 lumens.
20. 623 lumens.
21. 17 lumens/watt, 18.5 lumens/watt.
22. 450 lumens.
23. 2.19 ft.
24. 100 watt.

VIII POST-TESTS

Section A - Test 1

1. What sort of light source might give a mixture of line and continuous spectra (a continuous spectrum with brighter lines standing out?) Explain why.
2. Would you expect blue or green light to be more like red light? Why?
3. The following picture shows a portion of a wave. What is its wavelength?



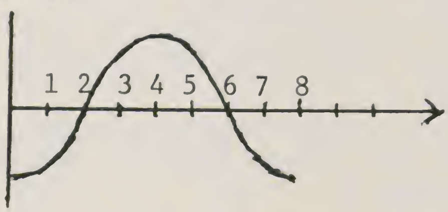
4. Why do most incandescent solids that you see glow red or yellow instead of green or blue?

Test 1 Answers

1. A source that includes both hot solids and hot gases mixed together. For example, the light from a dynamite explosion might have both.
2. Green light should be more like red because it is closer to it in the spectrum.
3. 6 cm.
4. Green or blue would indicate hotter than white-hot - solids under ordinary pressure would melt or vaporize.

Section A - Test 2

1. The aurora borealis (northern lights) is produced by charged particles, trapped in the earth's magnetic field, exciting the gases in the upper atmosphere near the north pole. What sort of spectrum would you expect the aurora to have?
2. In what natural phenomenon do you see the spectral colors, unmixed with non-spectral colors?
3. What is the wavelength of the wave shown?



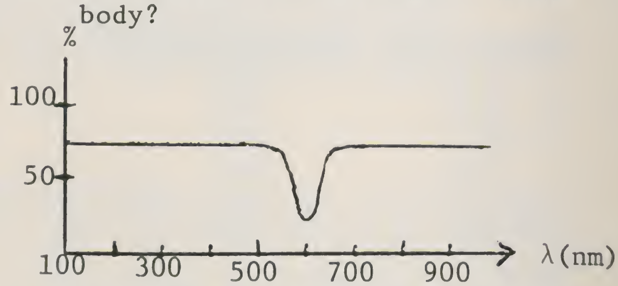
4. Because of high pressures due to gravity, stars emit spectra similar to those of hot solids. Are red giants hotter than white dwarfs? Explain.

Test 2 Answers

1. Line spectrum.
2. Rainbow.
3. 8 cm.
4. No. White dwarfs are hotter because the temperature of a solid is indicated by the color of emitted light.

Section B - Test 1

1. If the gas inside a light bulb is at 25°C when the lamp is off, what temperature would it have to attain when the lamp is turned on, to double the pressure?
2. A piece of iron wire has a resistance of .8 Ω at 0°C and 3.44 Ω at 600°C. What is its temperature coefficient of resistance?
3. The figure below shows a graph of percent of electromagnetic radiation absorbed versus wavelength for a solid. What change needs to be made to make this a graybody?



4. A manhole cover 1 m in diameter receives a power from the sun of 581 watts on a summer morning. What is the irradiance due to the sun incident on the cover?
5. What is the radiant exitance of a graybody with $\varepsilon = .4$ at a temperature of 1100 K?

Test 1 Answers

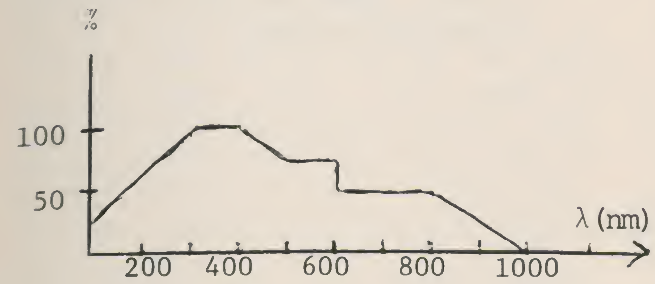
1. 596 K or 323°C.
2. $5.5 \times 10^{-3}/^{\circ}$C.
3. Increase the absorption of wavelengths around 600 nm (orange).
4. 740 W/m^2.
5. 3.32×10^4 W/m^2.

Section B - Test 2

1. A tin can is sealed with the air pressure inside at 15 psi at 30°C. If the can will burst when the

interior pressure reaches 75 psi at what temperature will it explode?

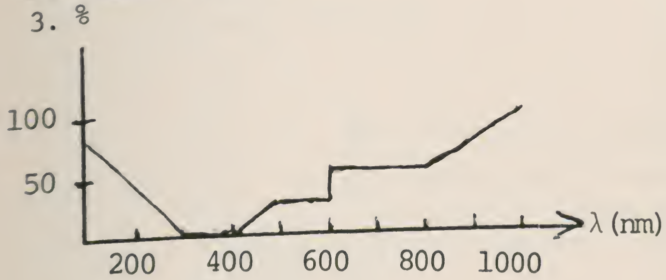
2. Using the graph in the text, what is the temperature of tungsten when its relative resistance is 5?
3. The figure below shows a graph of percent of incident electromagnetic radiation absorbed versus wavelength for a paint pigment. Sketch a similar graph for the least absorbing pigment that would have to be added to make the paint black?



4. A gray rooftop area of 50 m^2 receives a power of 3.5×10^4 W from the sun and it has an emissivity of .65. What will be the absorbed irradiance?

Test 2 Answers

1. 1515 K or 1242^{o}C.
2. About 1150 K.
3.



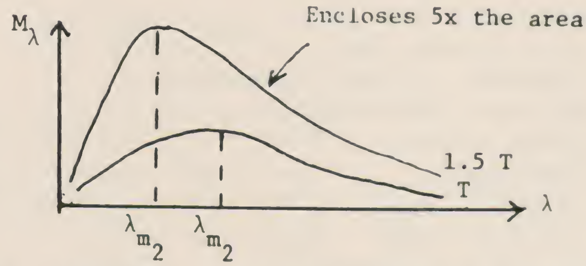
4. 455 W/m^2.
5. 357 K.

Section C - Test 1

1. What power is radiated from a tungsten filament of area 10^{-4} m^2 at a temperature of 2450 K in the wavelength interval between 2490 and 2510? Use Table 1.
2. Sketch spectral radiant exitance versus wavelength curves for a graybody at absolute temperatures $\underline{T}$ and 1.5 $\underline{T}$, making the peaks of the curves and the enclosed areas relatively correct.
3. Which appears brighter, a mW neon laser with λ = 633 nm or a 1 mW argon laser with λ = 488 nm? How much brighter? Use Figure 22.
4. A krypton laser is emitting 10 mW at λ = 522 nm. What is its luminous flux?
5. If the current through an incandescent lamp is increased until the filament melts at 3665 K, find the luminous flux just before it melts assuming ε = .3 and the area of the filament is 10^{-4} m^2. Use Figure 22.
6. How much luminous flux enters a window with area 1.5 m^2 exposed to full sunlight (100,000 lux)?
7. If you need 70 fc of illumination to read a book, how far away can you sit from a bare 100-W bulb (1700 lm)?

Test 1 Answers

1. .191 W.
2.



3. The 633 nm light appears 1.2 times brighter.
4. 5.1 lumens.
5. 15,345 lumens.
6. 150,000 lumens.
7. 1.39 ft.

IX LIST OF APPARATUS

Most of the equipment needed in this module is considered to be "normal" lab equipment and no source is listed for such items.

Item	Quantity	Source
Bunsen burner	1	
Lab stand with clamp	1	
Iron wire	1	
Copper wire	1	
Color comparator	1	Thornton Associates (construction is described later in this Teacher's Guide).
Clear, long filament, incandescent lamp	1	
Lamp socket	2	
D.C. Power Supply (0-200 volts, 0-1.0 A)	1	
D.C. Ammeter (0-1.0 A)	1	
D.C. Voltmeter (0-200 V)	1	
Ring stand	1	
Optical bench	1	
Component holder for optical bench	3	
Collimated light source	1	
Single slit	1	
Component table	1	
Prism	2	
Diffraction grating	1	
White screen	1	
Spectrometer (hand held)	1	
Mercury vapor lamp	1	
Fluorescent lamp	1	
Constant volume thermometer	1	
Mercury thermometer	1	
Large beaker	1	
Ohmmeter	1	
25-watt lamp	1	
Standard lamp	1	
Bunsen Photometer	1	

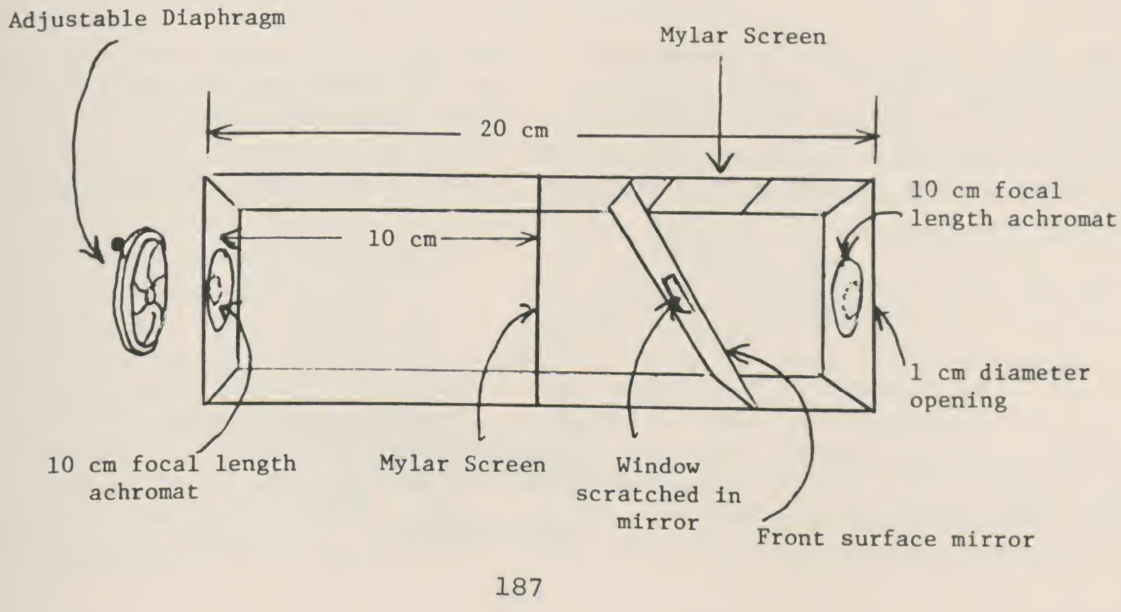
Construction of a Color Comparator

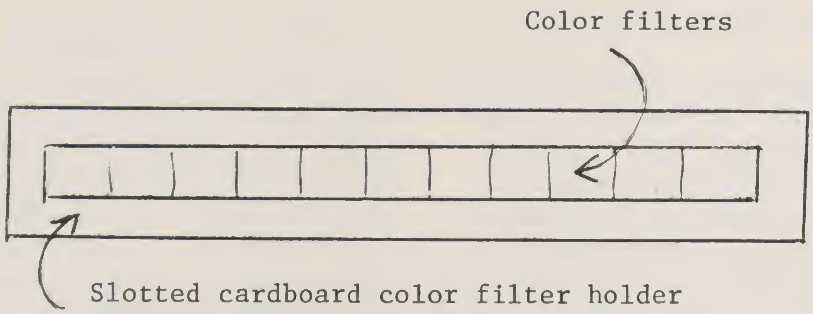
The color comparator compares "standard" color samples with colors viewed through the comparator lens. These colors viewed through the comparator will generally be from an incandescent source and will then range from red through yellow to white. Two methods of construction of a comparator as well as a simple alternative to it are suggested here.

The set of "standard" colors is made up of an arbitrary selection of red through yellow to light yellow to white colored panels that may be obtained from several sources including a local paint store. Even though the selection is arbitrary and will vary from person to person, once a set of "standards" is constructed for your lab the comparison with an incandescent source will be consistent. A very nice set of color charts with descriptive names such as "vivid red" and "deep red orange" may be obtained from the National Bureau of Standards; however, this set costs about eleven dollars. This set of standard colors is: ISCC-NBS Centroid Color Charts, Standard Sample No. 2106, National Bureau of Standards, Washington, D. C. 20234. A cheaper set of color filters which are used in a comparator whose construction is described later are available from Edmond Scientific. They are: Color Filters No. 40,675, Book of 44, Size 1 x 4 inches. These may be used in the same manner (reflected light) as the NBS color charts by backing the filter with white paper.

The simplest way to compare colors is to hand hold any set of standards up in front of the color source so that both the source and standard may be seen simultaneously. The difficulty with this method is that the student must alternately focus on the color sample and then on the color source. The purpose of a color comparator is to place both images on the same ground glass screen. A second purpose is to adjust the intensity of the source by means of an adjustable diaphragm at the front of the comparator.

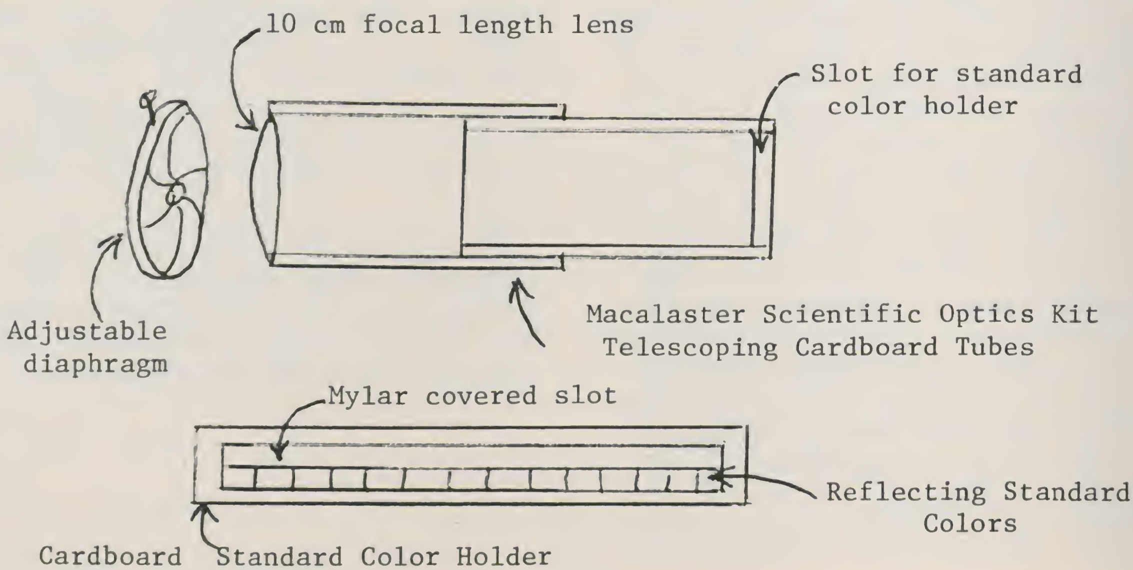
The color comparator described in the module uses transmitted light through the Edmond Scientific filters. The details of its construction are seen in the following figure:



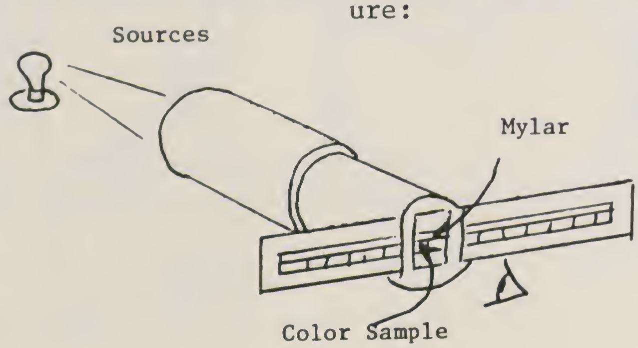


The comparator body is made of cardboard with the edges taped and the components taped into the body.

The details of a reflected light color comparator are shown in the following diagram:



The color comparator is assembled so that light from a source passes through the diaphragm and lens and is viewed on the mylar screen. The standard color holder is maneuvered through the slot until the reflected light from one of the standards compares to the light from the source which is viewed on the mylar screen adjacent to the standard as shown in the following figure:



CONTENTS

I. INTRODUCTION

The Laser module covers the physics concepts, definitions, and principles of light and its interaction with matter. The module emphasizes the following concepts: light sources, monochromaticity, spatial and temporal coherence, spontaneous and stimulated emission. A cursory discussion of atomic physics is included in Section C.

The principles treated include: the relationship of the speed of a wave to its frequency and wavelength, the superposition and interference of waves, and the relationship between energy transitions in an atom and the frequency of the emitted or absorbed photon.

The Laser module is divided into three separate sections. Each section is intended to form one week of instruction, and the module can be used for one week, two weeks, or three weeks, depending upon the needs and capabilities of your class. Although the module was designed for three weeks of instruction, there are several alternative ways in which it can be used.

	Week 1			Week 2			Week 3		
Student Characteristics	Sec.	Lab	Demo	Sec.	Lab	Demo	Sec.	Lab	Demo
High Ability	B	B-1,2	-	C	C-1	-	-	-	-
Better than Average Ability	B	B-1	-	B,C	B-2	-	C	C-1	-
Average Ability	A	A-1	-	B	B-2	B-1	C	C-1	-
Less than Average Ability	A	A-1	-	B	B-2	B-1	-	-	-
Class with no math prerequisites	A	A-1	-	-	-	-	-	-	-

The first section is largely qualitative. The student is introduced to some observations about light and its behavior at various material boundaries. He makes several observations which raise questions about the physics of light and its interaction with matter, but for which answers are not yet provided. The first section is concluded with a discussion of the advantages of laser light, some laser applications, and a summary of the qualitative principles and concepts he has learned. Two post-tests based on the goals of Section A of the module are included in Section VIII of the Instructor's Manual.

The second section of the module has the student arrive empirically at the relationship between the interference pattern and the slit width for both water waves and a particle box. He also determines the dependence of the water wave interference pattern and the wavelength of the water waves. The empirical equations are discussed quantitatively with appropriate problems

and exercises. The section is concluded with a discussion of coherent and incoherent light sources, monochromaticity, and a summary of principles and concepts the student has learned.

Section B has its own goals and post-tests which measure achievement of these goals.

Section C is a theoretical and analytical section. It defines bandwidth and derives the coherence length of a laser. A cursory discussion of atomic physics precedes the introduction to spontaneous emission, stimulated emission, and optical and collision pumping of lasers. Several optional sections are included, such as standing waves in a laser cavity, axial and non-axial modes, and line narrowing. The section is concluded with a summary of the principles and concepts learned in Section C. This section also has its own goals and post-tests.

II. SPECIAL PREREQUISITES

The module presents most of the optical principles necessary for an understanding of physical optics. However, the module has as a prerequisite some knowledge of transverse waves and the relationship between wavelength and speed for different frequencies. The Guitar module satisfies this requirement and serves as an excellent introduction to the Laser module. Some knowledge of chemistry would be helpful but not required before Section C on atomic physics is attempted.

A recent course in high school algebra is sufficient as a math prerequisite for this module. A course in college algebra is more than sufficient.

III. TABLE OF CONTENTS OF THE MODULE

- Bandwidth
- Coherence Length
- Interference Requires Coherence
- Experiment C-1. Spatial and Temporal Coherence
- Line Spectra of Gases
- Atoms and Light
- A Model of an Atom
- Photons
- The Wave and Particle Nature of Light
- Interaction of Electrons and Photons
- Spontaneous Emission
- Stimulated Emission
- Natural Linewidth
- Doppler Linewidth
- Inverted Population Needed for Laser Action
- Optical Pumping in Ruby Laser
- Pumping Scheme for He-Ne Laser
- Amplification between End Mirrors
- Standing Waves in the Laser (Optional)
- Axial and Non-Axial Modes (Optional)
- Coexisting Axial Modes (Optional)
- Line Narrowing (Optional)
- Other Lasers
- Summary

Work Sheets

- Experiment A-1
- Experiment B-1
- Experiment B-2
- Experiment C-1

IV. GOALS

The objectives of the <u>Laser</u> module have been included at the beginning of each section of the module. Each objective has been stated in general terms using common words, rather than the detailed, technical language of a behavioral objective. These statements are then called goals, rather than objectives. To meet the criteria one normally expects of objectives, a sample item has been included with each goal. When a student can demonstrate to himself that he can respond correctly to any item like the one given, he knows that he has met that objective.

Section VIII of this Manual contains tests which measure the achievement of samples of the goals for each section. These tests can be used to evaluate student performance weekly, or at the conclusion of their study of the entire module. A statement of these goals follows:

1. Explain the observational evidence for straight-line propagation of light.
2. Know the characteristics of interference patterns produced by thin films (e.g. a layer of air between two glass plates).
3. Know the characteristics of double-slit interference patterns.
4. Understand the concept of spectral or non-spectral color.
5. Know the special properties of laser light which make it more useful than ordinary sources in special applications.
6. Understand the implications of the wave and particle models of light.
7. Understand the correspondence of wavelength to color.
8. Know the relationship between the angular separation of the bright spots in Young's double-slit experiment, the wavelength of the light, and the slit separation.
9. Be able to calculate the frequency of light whose wavelength is given.
10. Understand the wave model explanation of temporal and spatial coherence.
11. Understand the concepts of bandwidth and fractional bandwidth.
12. Understand the concepts of coherence time and coherence length.
13. Understand the nature of spatial and temporal coherence required

for interference experiments.

14. Understand how the concepts of atomic energy levels and photons are related to the emission and absorption of light.
15. Understand the terms spontaneous emission, stimulated emission, natural linewidth, and Doppler linewidth.
16. Understand the concept of population inversion and the methods for achieving it.
17. Understand how the end mirrors of a laser produce a narrow bandwidth.

V. DISCUSSION OF ACTIVITIES

a. Laboratory Activities

Experiment A-1. Observation of Light.

The purposes of this experiment are: to demonstrate to the student the alternating light and dark bands and the color characteristics of the interference pattern using optical flats and a double slit with different light sources. The student is also introduced to collimation of a point source.

The apparatus needed for one set-up of Experiment A-1 is as follows:

Item	Quantities
Laser	1
Optical bench with associated component holders	1
Optical Flats	1 set
Lens (10-cm focal length)	1
Adjustable Diaphragm	1
Mirror	1
Double slits and single slits (a multiple-slit slide such as the one described in IX of this Instructor's Manual is recommended)	1 set
Clear, long-filament incandescent lamp	1
Lamp socket	1
Red filter	1
Blue filter	1
Point source of light	1

Experiment B-1. Particles and Waves.

The purpose of this experiment is to study the behavior of particles and of waves and compare the results with those for the behavior of light.

The apparatus needed for one set-up of Experiment B-1 is as follows:

Item	Quantities
Particle Demonstrator	1
Ripple Tank with accessories	1

Experiment B-2. The Interference of Light.

The purpose of this experiment is to discover the relationship between wavelength, slit separation, and the angular separation in the double-slit interference pattern.

The equipment needed for one set-up of Experiment B-2 is as follows:

Item	Quantities
Laser	1
Double slit - single slit slide (same as in Experiment A-1).	1

Experiment C-1. Spatial and Temporal Coherence.

The purpose of this experiment is to compare the spatial and temporal coherence of a laser with that of ordinary light sources.

The equipment needed for one set-up of Experiment C-1 is as follows:

Item	Quantities
Optical Bench with component holders	1
Laser	1
Incandescent Lamp	1
Frosted glass	1
Double Slit	1
Michelson Interferometer	1
Mercury light source	1
Green filter	1
Lens (short focal length microscope objective works well)	1
White screen	1

b. Other Activities

The Laser module has been designed for use in an introductory physics course which has two or three hours of laboratory time per week and three fifty-minute classes per week. This module is most appropriate in the second semester physics course. The subject matter, physical optics and modern physics, is typically treated in the second semester. However, the module may be used at any point in a course, but should be used after the prerequisites listed in the module or in Section II of this Instructor's Manual have been met.

Physics of Technology modules can be used most effectively if you avoid lectures. Class time can be most interesting and helpful to students if you will spend that time doing demonstrations, discussing the laboratory work, and asking students about questions and problems in the module. A list of resource material follows.

c. Resource Material

A. 16-mm Sound Film

1. "Conquest of Light", Bell Telephone Labs, Murray Hill, N.J.
2. " Demonstration of Interference of Waves in a Ripple Tank"; Purdue Univ. A.V. Center, Lafayette, Ind.
3. "The Laser: A Light Fantastic"; Film Associates of Calif.
4. "Laser Light"; Scientific American.
5. "Lasers"; Time-Life Films, New York, N. Y.
6. "Introduction to Holography"; Encyclopaedia Britannica Educ. Corp.

B. 8-mm Film Loops

1. "Michelson Interferometer"; E.B.E. Corp.
2. "The Spectrum of the Hydrogen Atom"; E.B.E. Corp.
3. "Diffraction at an Aperture (Fixed Wavelength)"; Gateway Educational Films, London, England.
4. "Diffraction at an Aperture (Wavelength Varied)"; Gateway.
5. "A Wave Equation"; Gateway.

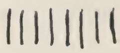
C. Transparencies

1. "Huygens' Principle"; Wiley.
2. "Interference" (Series of Four); 3M, St. Paul, Minn.
3. "Interference and Diffraction"; McGraw-Hill Films, New York, N.Y.
4. "Interference, Constructive and Destructive"; Keuffel & Esser.
5. "Energy Level Diagram for Hydrogen Atom"; Modern Learning Aids, New York, N.Y.
6. "Holography" (15 transparencies); Lansford Publishing Co., Calif.

VI. SAMPLE DATA

Experiment A-1.

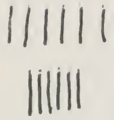
Part I

1. Yes.
2. Yes. The spectral colors.
3. 
4. 
5. It has dark and bright bands.
6. The pattern is brighter.
7. Just red.
8. The pattern rotates.
9.  Thinner lines.
10. The bands are more distinct.
11. Dark band.

Part II

1. I see no slits. The light is pretty uniform.

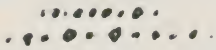
2. I just see the long filament.
3. The filament splits into alternating bright and dark bands, with the outer ones being colors.
4. I see the spectral colors. The colors run from blue out to red.
5. No. The red bands are farther apart than the blue bands.



red

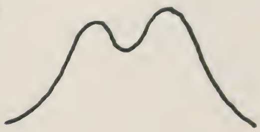
blue

6.

7. Red only.
8.  Different spacings.
9.
10. 
11. Yes. The center band is broader than others for the single slit. The double slits give even patterns.

Part III
1. .2 or .3 cm.
2. .5 to .6 cm.
3. About 2.3.
4. .4 cm.
5. .4 cm.
6. 1.
7. The laser spreads out less.

Experiment B-1
Part I
1.



2. Smaller.
3.

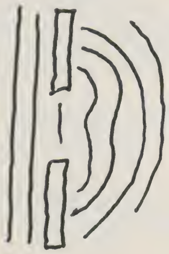
4. Decreased.
5.

6.

7. More narrow.

Part II
1.

2. Dark is maximum activity. Light is minimum.
3. Maximum.
4. About 25°.
5. No. The angle is larger.
6. About 35°.
7. The spread increased as the distance between slits decreased.
8. It appears to spread out the pattern.
9.



10.

11. Appears to become wider.
12. Same as above.
13. Yes.

Part III

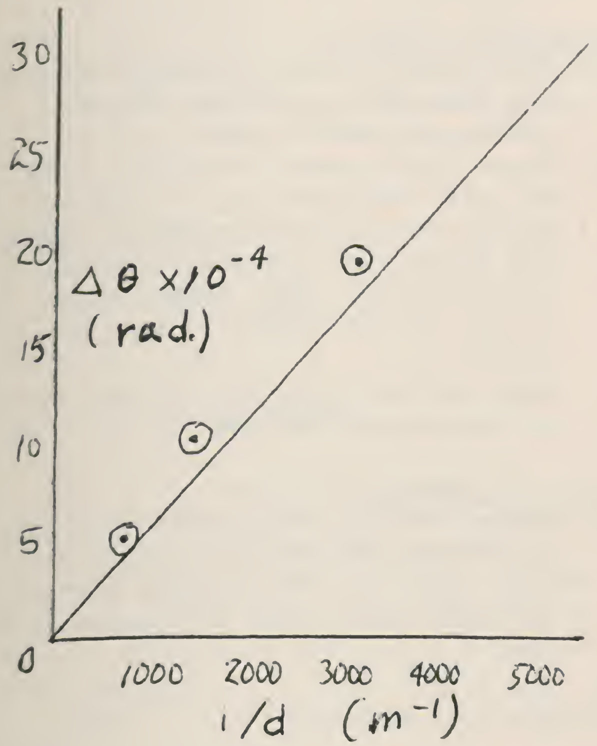
1. Waves.
2. The narrower the slits, the more the pattern spreads out with water and light.

Experiment B-2

1. $\underline{a}$ = 0.0066 m.
2. $\Delta\theta$ = 0.0033 radians.
3. $\underline{d}$ = 0.00017 m.

Trial	$\Delta\theta$	$\underline{d}$(m)
1	0.0033	0.00017
2	0.0018	0.00032
3	0.0010	0.0007
4	0.0005	0.0014

4. $\Delta\theta$ decreases.
5. Yes. See graph below.



6. Slope = 6.2×10^{-7} m.
7. Meters.

Experiment C-1

Part I

1. Yes.
2. Yes. It fades out.
3. No. (Note: the spatial coherence improves as the double slits are moved away from a source, since the wave fronts tend to smooth out with distance.)
4. Yes.
5. No.
6. Much longer distance of coherence with the laser.

Part II

1. They move outward and disappear at the edges as new ones appear in the center. A few millimeters.
2. It is only a few millimeters.
3. Much lighter.
4. It is very much longer than the mercury-vapor light.
5. Laser's coherence length is 10 or 100 times more than the mercury-vapor light.

VII. SOLUTIONS TO PROBLEMS

The problems and questions are an important part of the module. Questions should be discussed in class, so far as possible. Many of the problems should be discussed in class, but if answers are provided, many students will work the problems outside of class and check their own work. The problem answers below are provided so that you can copy them and distribute them to students, if you wish.

1. 4.0×10^{-7} m.
2. 160 cm = 1.6 m.
3. 400 nm, 700 nm.
4. 7.5×10^{14} Hz, Violet.
5. 1.3×10^{-15} m = 1.3×10^{-6} nm.
6. 0.15 m.
7. 3.2×10^{-12} m = 3.2×10^{-3} nm.
8. 2.5×10^{-4} m = 0.25 mm.

9. 4.0×10^{-19} J.
10. 16.33×10^{-19} J.
11. 4.5×10^{14} Hz.
12. 20 cm, No.
13. 2×10^{6}.

VIII. POST-TESTS

Section A - Test 1

1. What are the differences between laser light and ordinary light sources?
2. List several properties of the behavior of light.
3. What are some applications of laser light?

Test 1 - Answers

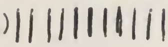
1. Laser light contains only one spectral color instead of all colors for most light sources. Laser light produces clearer interference patterns than ordinary light. Laser light has better collimation than ordinary light.
2. Light travels in straight lines. Light contains different colors, and white light contains all the spectral colors. Different parts of a light beam may be made to interfere with each other.
3. Drilling small holes, repairing detached retinas, range finding, alignment and holography.

Section A - Test 2

1. What evidence can you cite that light travels in straight lines?
2. A blue light beam is shined on top of two glass plates. You observe a dark band directly above the plates at a certain point. What would you observe below the plates directly under this dark band?
3. A laser beam is shined through a grating having 5000 slits per centimeter. a) What would you observe on a screen placed on the other side of the grating (make a sketch)? b) If the grating were replaced by one having 10,000 slits per centimeter what would you observe (make a sketch)?
4. Which of the following are spectral colors? Why are the others non-spectral colors? Brown, red, yellow, orange, pink, blue.

Test 2 - Answers

1. Point sources cast sharp shadows.
2. A bright band would be directly below the dark band.
3. a)  5,000

   b)  10,000

4. Red, yellow, orange, and blue are spectral colors. Brown and pink are not found in the visible spectrum.

Section B - Test 1

1. Which model (waves or particles) do you feel best describes the behavior of light? Why?
2. Laser light passes through a pair of slits separated by 0.03 mm producing an interference pattern with the first spot 1 degree from the central spot. What is the wavelength of the light? ($\sin 1^{\circ} = 0.018$.)
3. What is the frequency of red light of wavelength 600 nm?

Test 1 - Answers

1. Waves, because the double-slit interference pattern for light is more like the interference pattern in water waves than in the particle box.
2. 5.4×10^{-7} m.
3. 5×10^{14} Hz.

Section B - Test 2

1. What color corresponds to each of the following wavelengths of electromagnetic waves? 400 nm, 555 nm, 700 nm.

2. A pair of slits has a separation of 0.2 nm. When light of a certain color passes through the slits, alternating spots of light appear on a screen 2 meters from the slits. These spots are 5 mm apart. What is the wavelength of the light? Express your answer in nm.
3. What is the frequency of violet light of wavelength 400 nm?

Test 2 - Answers
1. Violet, Green, Yellow.
2. 500 nm.
3. 7.5×10^{14} Hz.

Section C - Test 1
1. A CO_2 laser has a band width of 0.0001% of the average wavelength of 10,600 nm. What range of wavelengths are in the laser light?
2. What is the energy of a photon if its frequency is 4×10^4 Hz?
3. A laser emits wave trains which are 10,000 waves long with a wavelength of 500 nm. What is the coherence time of this source?

Test 1 - Answers
1. $\Delta\lambda = 1.06 \times 10^{-2}$ nm.
2. $E = 2.64 \times 10^{-19}$ J.
3. $\Delta t = 1.7 \times 10^{-11}$ s.

IX. LIST OF APPARATUS

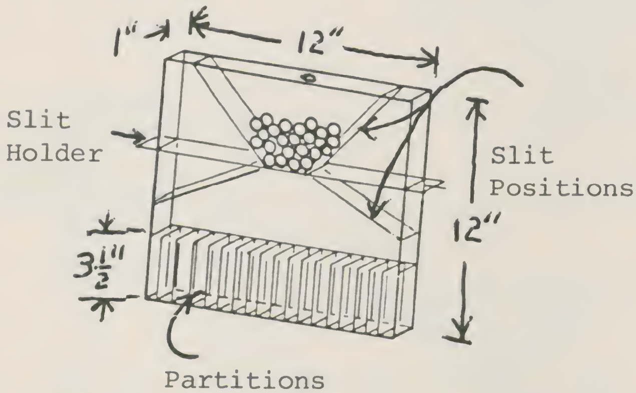
Most of the equipment needed in this module is considered to be "normal" lab equipment, and no source is listed for such items. The particle box may be constructed in your lab according to the directions given at the end of this section.

Item	Quantity	Source
Laser	1	
Optical bench with associated component holders	1	
Optical Flats	1 set	
Lens (10-cm focal length	1	
Adjustable diaphragm	1	
Mirror	1	
Double & single slits	1 set	National Press (or see discussion at end of this section)
Incandescent Lamp (clear, long filament)	1	
Lamp socket	1	
Red filter	1	
Point source of light	1	
Particle Box	1	Thornton Assoc. (or see discussion at end of this section)
Ripple tank with accessories	1	Macalaster Scientific Corp. (or equivalent)
Frosted glass	1	
Michelson Interferometer	1	
Mercury Light Source	1	
Green Filter	1	
Lens (Short focal length microscope objective works well)	1	
White screen	1	

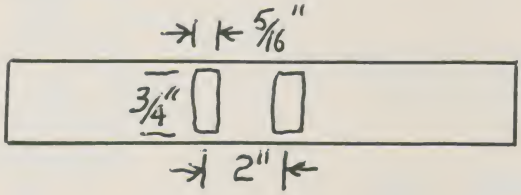
Particle Box Construction

The particle box is constructed of clear 1/8-inch Plexiglas using Plexiglas glue to make the seams. The inside pieces as well as side walls are all constructed of 1-inch-wide material as shown in the figure. A 12-inch by 12-inch cover plate is glued to the front and back of the box. Twenty partitions, 3 1/2 inches long

and 1" wide, are equally spaced across the bottom. The slanted slit positioners are each 5 1/2 inches long.



The slit holder is made of the 1/8-inch Plexiglas 14 inches long and just under 1 inch wide. The width must be trimmed to allow moving through the slots in the side walls of the box. The slit dimensions are shown in the figure.



Several slit widths may be constructed so that the relationship of particle pattern to slit width may be studied. Several different width single slits should be constructed also.

<u>Double-and Single-Slit Optical Slide</u>

Several different slit widths for single-slit diffraction and several widths of double slits are needed for Experiment C-1. These slits may be constructed using microscope slide glass which has been painted with a graphite in alcohol solution. The slits are made once the solution has dried using a razor blade as described in the PSNS text.

The authors recommend, however, that a commercially prepared slide be purchased. A very nice one is available from: National Press, Palo Alto, California. This slide contains several different single slits and double slits as well as several diffraction gratings. The three smallest double-slit separations are 0.017 cm, 0.033 cm, and 0.070 cm.

CONTENTS

I INTRODUCTION

This module introduces a number of basic concepts regarding the nature and behavior of sound waves. The student also obtains a working knowledge of technical matters pertaining to sound production, including the physics underlying loudspeaker design and construction. A motivating factor for many students will be the discussion of loudspeaker specifications from a physics standpoint, by which a better understanding of "high-fidelity" can be gained.

In Section A the emphasis is on the loudspeaker itself. The speaker is approached as a simple type of electrodynamic "machine", and the analogy of dynamic speakers and mikes to motors and generators is discussed. The student measures the force and displacement of a speaker diaphragm due to currents in the voice coil. From the force, the strength of the magnetic field in the magnet gap can be deduced.

In Section B, attention shifts to the features of sound radiation, especially the spatial pattern of sound intensity surrounding a speaker. Among other things, the decrease of intensity with distance is measured, leading to a discussion of the Inverse Square Law of Radiation.

Section C emphasizes the wave nature of sound, and shows how wave properties such as reflection and interference can be useful in practice: for intrusion sensors, echo range finders, etc. In the experiments, sound reflections are first studied qualitatively. Then a standing wave pattern is formed and used to measure the wavelength and, from that, the speed of sound.

II SPECIAL PREREQUISITES

There are no special prerequisites for this module, except that for the Physics of Technology series as a whole: high school algebra.

III TABLE OF CONTENTS OF THE MODULE

SECTION B: Measuring Sound Radiation

Sound Sources Are Not Isotropic
Detectors Are Also Anisotropic
Measuring Patterns Of Sound
Experiment B-1. Measuring The Pattern Of Radiation
Experiment B-2. Measuring The Effect Of Distance
Experiment B-3. (Optional): Family Of Isointensity Plots
Experiment B-4. (Optional): Directional Character Of The Mike
Experiment B-5. (Optional): Spherical Radiators
Data Analysis And Discussion
Examining Your Results
Loudspeaker Specifications
Summary
Questions And Problems

SECTION C

Introduction
The Speed Of Waves
Experiment C-1. Observing Reflections Of Sound Waves
Experiment C-2. Using Reflections To Measure The Wavelength
Experiment C-3. Using Reflections To Detect Intrusion
Experiment C-4. (Optional): Echo Ranging With Sound Pulses
Experiment C-5. (Optional): Phasing Two Speakers
Experiment C-6. (Optional): Standing Waves Without Reflections
Experiment C-7. (Optional): Producing Beats
Data Analysis And Discussion
Visualizing Wave Motion
Interference
Mathematics Of Waves (Optional)
Summary
Questions And Problems

IV GOALS

The objectives of the Loudspeaker module have been included at the beginning of the module.

V DISCUSSION OF ACTIVITIES

The module is divided into three Sections, each representing about one week's study. It assumes that approximately three class hours and two lab hours will be devoted to each section. A recommended scheduling of class and lab activities, and content of class periods, is as follows:

First Class Period

This should orient the student to the topics that will be covered in the section and to the experiments that will be performed. It should include background material, for example a short film about the topic, and a discussion of the lab experiments and apparatus that will be used.

Laboratory Session

The laboratory experiments should be done before the week's final two class sessions. They generally can be done in a two-hour lab period, though slower-working students may take somewhat longer.

Second Class Period

This should discuss the laboratory activities and the data taken. The students should be helped in graphing and analyzing their results and in understanding the behavior in terms of the underlying physical laws or principles. If the optional experiments were not done by the students, they can be done here as demonstrations. Problems and Questions can be assigned at this time.

Third Class Period

This should continue the discussion of the physics underlying the device behavior. The assigned Questions and Problems can also be discussed. It is often a good idea to end this class with a short 20-minute quiz on the section's work.

The following are specific notes and suggestions relating to each section:

SECTION A

From the work here one should get a feeling for magnetism, especially the magnetic force on a current-carrying wire, even if this has not been previously studied. The initial activity of "exploring the magnetic field" with a compass should not be neglected, even though it is not counted among the actual experiments. The teacher may wish to stress that where the field direction changes very rapidly with position (e.g., in the region near the speaker's magnet gap), a very small compass would be required to indicate the true direction at any one position. Otherwise, some average over a range of positions is obtained.

NOTE: Many students will find that it aids considerably in trying to visualize the speaker's construction to look at a dismantled version. It is advisable to provide this for inspection during the first lab period.

In Experiment A-1, a purpose, in addition to the stated one of becoming familiar with the instrumentation, is to sample a few different audio signals and to hear the differences in the sound they produce. Especially important is Step 4 of the procedure, where various frequency settings of the audio oscillator are tried. The concept of sound frequency is not formally introduced until much later in the discussion (in Section B). It is hoped that, by that time, the student will already be comfortable with the operational meaning of frequency and its connection with musical pitch. It is not absolutely necessary to view the audio waveforms on an oscilloscope, but it is extremely helpful.

Experiment A-2 measures the static deflection of the speaker diaphragm for various coil currents up to about 0.5A, while Experiment A-3 "nulls out" the deflections by placing known weights on the diaphragm. A point to note in both experiments is that small currents should be used first; this is because some elastic hysteresis may develop at the largest values of current, partly due to heating of the diaphragm material near the coil. Students should also be cautioned about exceeding .5A in the speaker coil since it is possible to burn it out.

SECTION B

The experiments here use a microphone to measure the speaker's pattern of sound intensity under various conditions. The mike's output AC signal can be measured directly on a scope, or it can be rectified and measured on a DC meter. In either case, some pre-amplification will be required, since the original amplitude is likely to be only a few millivolts at most.

As described in the module, a simple meter rectifier can consist of one ordinary diode in series with the pre-amp output. The only point to emphasize is that the pre-amp offset must then be adjusted so that even with zero sound intensity into the mike, there is a small positive reading on the meter. This pre-biases the diode in the "forward" (i.e., conducting) direction, and assures that even a small increase of sound input will affect the meter reading. Otherwise, there will be a "dead band" of low input intensities over which the meter does not respond.

While it might be feared that the sound intensity measurements at one station would be grossly altered by sounds coming from adjacent stations, this is not the case if minimal precautions are taken. A few helpful precautions are detailed in the lab instructions. The reason why the problem is not more serious is that whereas such unwanted sounds may be loud enough to be easily detected by the human ear, they do not have sufficient intensity to count for much in the microphone pickup. This fact can be used to emphasize the differences between loudness and intensity.

SECTION C

In Experiment C-1, the specular reflection of sound waves off a fairly large, flat board is observed. Naturally, what is really involved here is a diffraction pattern, with a peak in the "specular" direction. The peak becomes more dramatic at shorter wavelengths, which is why a sound frequency of 1000 Hz is recommended to start with. If the teacher wishes to lecture on the topic of diffraction (not covered in the module), it would be useful to supplement this with a more thorough investigation by the student of the frequency dependence of the reflected pattern.

Experiment C-1 is an optional one, dealing with the use of echoes for range finding. This is more delicate than most of the other work in the module, if only because of the increased importance of proper synchronization of the oscilloscope. However, the more capable student should not find any insurmountable difficulty here if enough time is allotted. One point to be noted is that careful alignment of the echo-producing surface is useful to maximize the reflected signal at the mike. Also, moving the surface closer to, or farther from, the mike, while maintaining good alignment, may reveal the expected "signal" on the scope even in the presence of substantial "noise".

VI SAMPLE DATA

SECTION A

Experiment A-2. Measuring Motion Of The Diaphragm

A sample graph is given in the module (Figure 18).

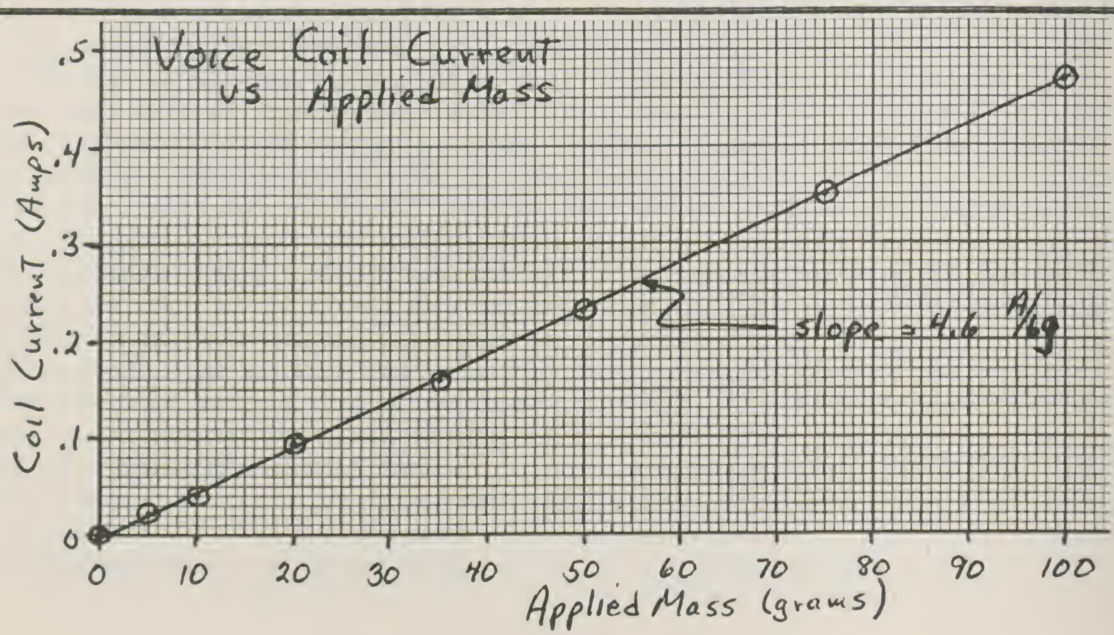
Experiment A-3. Measuring The Force Of The Voice Coil

A portion of a sample graph is given in Figure 21 of the module. The complete graph is shown below as Figure 1. The slope of the line is 4.6 A/kg, giving an inverse slope 0.22 kg/A. Multiplying this by 9.8 N/kg, for conversion from mass to weight, gives 2.1 N/A. Thus, following the procedure of the worksheet, the field in the gap is calculated as:

$$\underline{B} = \left(\frac{1}{3.2\ \text{m}}\right) \frac{\underline{F}}{\underline{i}}$$

$$= \left(\frac{1}{3.2\ \text{m}}\right) \times (2.1\ \text{N/A})$$

$$= 0.66\ \text{T}$$



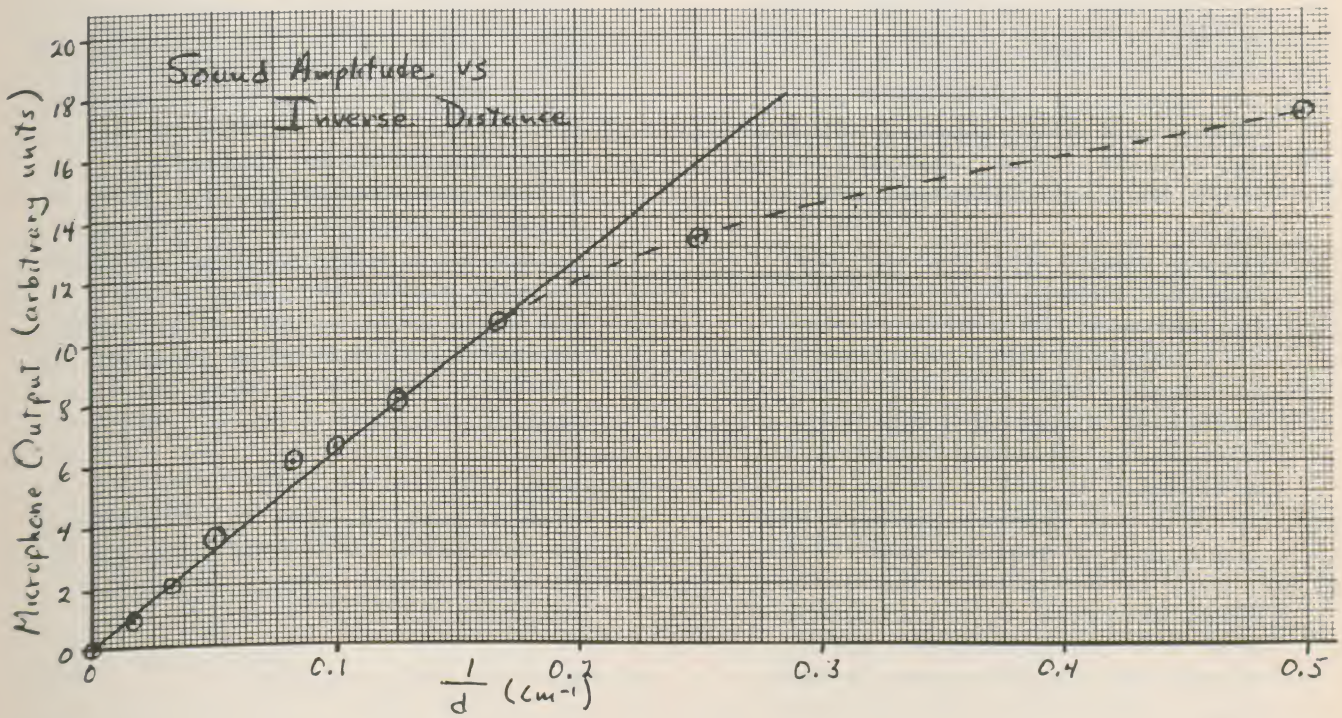
SECTION B

Experiment B-1. Measuring The Pattern Of Sound

A typical isointensity plot for the planar speaker is shown in the preface to the module.

Experiment B-2. Measuring The Effect Of Distance

Figure 2 below shows sample data for the sound amplitude directly in front of a planar speaker, at several different distances ranging from 2 cm up to 60 cm. The amplitude is represented in terms of a suitably amplified microphone output voltage. The data are plotted versus inverse distance, as suggested on page 36 in the module. For reasonably large distances (small d^{-1}) the plot is linear, as should be the case if the "Inverse Square Law" of intensity holds. The law breaks down extremely close to the speaker's diaphragm (d < 4 cm). This is not surprising, since the distances and angles to various parts of the diaphragm are quite different.



SECTION C

Sample Data for Experiment C-3 is given in Figure 66 and the accompanying discussion.

VII SOLUTIONS TO PROBLEMS AND QUESTIONS

SECTION A

Questions

1. The light spot can be viewed at a large distance from the mirror. Thus a very small angle of deflection produces a displacement of the spot which can be easily measured and compared with other displacements.
2. Null measurements eliminate unknown variables and avoid distortions of the measured system. Also, they may enlarge the permissible range of the measured variables.
3. If the speaker's response is not linear, the addition of two separate electrical signals will not produce a sound which is a sum of the corresponding individual sounds. Thus combinations of tones will be distorted, for example.
4. Force, electrical current, and magnetic field.
5. The movement of a coil of wire in a magnetic field produces a voltage in the coil. In the "reverse" situation, applying a voltage to the coil produces movement.
6. In both the dynamic speaker and the motor, a voltage applied to a coil in a magnetic field produces movement. In the dynamic mike and the generator, moving a coil in a field produces voltage.

Problems

1. Approximately, $\sin 2\alpha = .012\text{m}/1\text{m}$

$$= .012$$

Thus: $\underline{d} = (8\text{cm})(\sin\alpha) = .5 \text{ mm}$

2. $\underline{F} = \underline{B} \times \underline{i} \times \ell = (4\text{T}) \times (1\text{A}) \times (1\text{m})$

$$= 4\text{N}$$

3. $\ell = (2 \text{ layers}) \times (50 \text{ turns/layer}) \times (\pi \times 1\text{cm/turn})$

$$= 314 \text{ cm}$$

$$= 3.14 \text{ m}$$

4. $\underline{F} = \text{Weight} = \underline{mg}$

$$= (.075\text{kg}) \times (9.8\text{N/kg})$$

$$= 0.74 \text{ N}$$

SECTION B

Questions

1. A circle, with source at the center.
2. A long, thin "lobe" pointing in the forward direction.
3. The listener's impression of the sound will be variable, depending upon where he is sitting or in which direction he is facing.
4. A family of isointensity plots gives information about the variation of intensity with distance in many different directions.
5. The microphone sensitivity changes if the mike is rotated relative to the line joining it with the source.

Problems

1. From Figure 23, 100 dB corresponds to intensity 10^{-2} W/m^2, and 20 dB to 10^{-10} W/m^2. Thus, intensity ratio is $10^{-2}/10^{-10} = 10^8$.

2. $\underline{E} = (\underline{P}_{out}/\underline{P}_{in}) \times 100\%$

$$= 0.5/100 \times 100\%$$

$$= 0.5\%$$

Probably a "dynamic" speaker.

3. Converter input = output ÷ gain

$$= (10 \text{ mV}) \div \left(\frac{50 \text{ mV}}{1 \text{ mV}}\right)$$

$$= 0.2 \text{ mV}$$

SECTION C

Questions

1. One-half wavelength = 15 cm.
2. Sound reflections from the walls create standing waves. The standing-wave pattern is different at different frequencies. Thus the spectrum of the speaker's sound is altered by the room characteristics.
3. Yes. This effect is used deliberately in certain auditoriums.

Problems

1. $\lambda = \frac{v}{f} = (344\ \frac{m}{s}) \div (1545\ s^{-1})$

$= 0.223$ m

2. Speed = distance ÷ time

$= \frac{2\ell}{t}$

$= \frac{.30\ m}{.0005\ s}$

$= 600\ \frac{m}{s}$

3. Length = one-half wavelength

Thus $\lambda = 2\ell = 2m$

$v = f\lambda = (400\ Hz) \times (2m)$

$= 800\ \frac{m}{s}$

VIII POST-TESTS

Test I

1. Name three essential parts without which a dynamic speaker could not function.
2. Why does a dynamic microphone produce a voltage when exposed to sound?
3. How does a speaker's magnetic field compare to earth's magnetic field? Is it much stronger, much weaker, or about the same?
4. What magnetic field strength in the magnet gap is required to produce a force of 1N on a coil 2m long carrying a current of 0.5A?
5. How can there be an isointensity ("equal" intensity) curve for a speaker, when the power radiated is different in different directions?
6. If one sound is 2 bels louder than another, how much greater is its intensity?
7. One listener is sitting 3 times as far from a speaker as another (on-axis). The sound received by the first is therefore weaker. Roughly, what should be the ratio of the:
   a) intensities?
   b) amplitudes which each receives?
8. The sound intensity at the "threshold of hearing" is about 10^{-12} W/m^2. If the area of the eardrum is assumed to be 1 cm^2, how much *power* is detected at the threshold of hearing?
9. What is meant by the term "specular reflection"? Explain as clearly as possible.
10. Define the unit "one hertz".
11. Write down the equation giving the fundamental relation between wave speed, wavelength, and frequency.
12. If the frequency of a periodic sound wave is 3000 Hz, what is its *period*?
13. The speed of sound in air is about 344 m/s. If a person in a boat shouts, and the echo from shore is heard 0.5 s later, how far away was the echo reflected?
14. What is a "node" of a sound wave? Does every sound wave have nodes? If not, which ones do not?
15. Should the "bass" (low-frequency) strings of a piano be longer or shorter than the "treble" (high-frequency) strings? Why?

Test II

1. Why can a "dynamic" speaker also be used as a microphone? (Hint:

base your answer on the Principle of Induction.)

2. A hi-fi amplifier provides 30W of electrical power to a speaker. The speaker's efficiency is 1-1/2%. What is the value of acoustical power coming from the speaker?
3. Why is a magnet needed in a dynamic loudspeaker?
4. The earth's magnetic field is about 0.5×10^{-4} T. Estimate the force due to earth's field on a loop of wire 1 m long carrying a current of 0.5A.
5. The sound intensity radiated by a speaker 30° from the main axis is one-fourth the on-axis intensity, at equal distances. If an isointensity plot is begun at 150 cm from the speaker on the axis, estimate its value in the 30° direction. (Hint: use the "Inverse Square Law".)
6. What is the loudness difference between two sounds, in dB, if the intensities are 5×10^{-6} W/m^2 and 5×10^{-8} W/m^2?
7. If the total sound power radiated by a speaker is 0.25W, how much energy is radiated in 3s?
8. If the sound from a speaker obeys the Inverse Square Law of Radiation, why does the voltage from a mike picking up the sound not show the same "inverse square" dependence on the distance? What dependence does it show?
9. Define as precisely as possible the "period" of a periodic wave.
10. Sound from a speaker is reflected back on itself by a large board. A standing wave is formed between the speaker and the board. The spacing of nodes is 21-1/2 cm. What is the wavelength of the sound?
11. In the previous question, what must be the frequency of the sound wave? (The speed of sound is 344 m/s.)
12. In your music listening room at home, you discover that there are certain "dead spots" in the room for particular tones. Should you try to increase or decrease the sound reflections from walls, ceiling, etc.? Explain.
13. About 3 seconds after seeing a flash of lightning, you hear thunder. How far away was the lightning?
14. The speed of sound in water is about 3 times the speed in air. When sound of a certain frequency enters water, the frequency remains the same. What happens to the wavelength?
15. What features of the air increase and decrease very rapidly when a sound wave is present? (Name at least two.)

<u>Solutions To Post-Tests</u>

<u>Test I</u>

1. Magnet, coil, and diaphragm.
2. The diaphragm is forced to vibrate by the pressure variations. The coil moves with the diaphragm. This movement in a magnetic field creates a voltage.

3. About 10^4 times stronger in the gap.

4. $\underline{B} = \dfrac{\underline{F}}{(\underline{i} \times \ell)}$

$= \dfrac{1N}{(0.5A \times 2m)}$

$= 1T$

5. The intensity also varies with distance in each direction. Thus at different distances, the intensities in different directions may be equal.
6. 100 times greater.
7. a) 1/9
   b) 1/3

8. $\underline{P} = \underline{IA}$

$= (10^{-12}\ W/m^2) \times (10^{-4}\ m^2)$

$= 10^{-16}\ W$

9. Angle of incidence = angle of reflection.
10. "One hertz" means one complete repetition or cycle per second.
11. $\underline{s} = \lambda \underline{f}$.
12. 0.33×10^{-3} s.
13. Round trip = twice distance.

Thus: $\underline{D} = \frac{1}{2} \times \underline{s} \times \underline{t}$

$= \frac{1}{2} \times (344\ \frac{m}{s}) \times (0.5s)$

$= 86$ m

14. A place where the pressure variations are zero.
 No; traveling waves.
15. Longer; because length = $1/2\lambda$, and since $\lambda = \underline{s} \div \underline{f}$, low frequency means long wavelength.

Test II

1. Because sound vibrations cause the diaphragm and coil to move. A moving coil in a magnetic field creates a voltage.

2. $\underline{P}_{out} = \underline{E} \times \underline{P}_{in}$

$= .015 \times 30$ W

$= .45$ W

3. To force a current-carrying wire (the coil) to move the diaphragm.

4. $\underline{F} = \underline{B} \times \underline{i} \times \ell$

$= (0.5 \times 10^{-4}\ T) \times (1m) \times (0.5A)$

$= 0.25 \times 10^{-4}$ N

5. 75 cm (1/2 distance gives 4 times intensity).
6. 20 dB.
7. 0.75 J.
8. Mike voltage proportional to amplitude; "Inverse First Power" Law.
9. The length of time between repetitions at a given place.

10. $\lambda = 2 \times 21\text{-}1/2$ cm

$= 43$ cm

11. $\underline{f} = \frac{\underline{s}}{\lambda}$

$= \frac{344\ m/s}{.43\ m}$

$= 800$ Hz

12. Decrease reflections, to lessen interference which causes standing waves.

13. $\underline{D} = \underline{s} \times \underline{t}$

$= (344\ \frac{m}{s}) \times (3s)$

$= 10^3$ m

14. 3 times larger.
15. Pressure, density, and temperature.

IX LIST OF APPARATUS

SECTION A

1. Loudspeaker — preferably an approximately 8-ohm polyplanar type dynamic speaker, for example the Lafayette Model P5LR. This is available from any local Lafayette Radio store or from the central facility:

 Lafayette Radio Electronics
 111 Jericho Turnpike
 Syosett, Long Island, N.Y.
 11791

 The polyplanar speaker is recommended because it is extremely rugged and can take student abuse. However, any dynamic loudspeaker can be used provided that suitable precautions are taken to protect the paper cone.

2. Compass needle
3. Audio signal generator or oscillator: 300 Hz - 50 kHz.
4. Oscilloscope (recommended but not required)
5. Microphone: crystal type, for example the Lafayette #99-45874
6. Amplifier and Pre-amp: Gain ≈ 2000, for example the Thornton APS amplifier and TTA pre-amplifier. Available from:
   Thornton Associates
   87 Beaver Street
   Waltham, Massachusetts
   02154
7. Ammeter: 0 - .5A, DC
8. DC power supply (or batteries): variable 0 - 10V @.5A
9. Small spherical mirror: $d \approx$ 2-3 cm, $f \approx$ 20-30 cm (or flat mirror and lens)

   Light source: for example a flashlight or optical bench light source.
10. Set of weights: 1 - 100g

SECTION B

Items 1, 3, 5, 6 and 7 of Section A plus:
Diode: For example 1N4148
Protractor

SECTION C

Same as Section B plus:
Hardboard panel: approximately 1m square
Sound insulation: for example sound-absorbing ceiling tile or fiber glass insulation
Hardboard box: approximately 1m x 1m x 1m
<u>Optional</u>:
  Square-wave pulse generator: <10 Hz
  Oscilloscope

CONTENTS

I INTRODUCTION

In this module the basic principle of direct current electricity and its measurement are treated through the use of the multimeter. To get the most out of the module, the student should be encouraged to do as much experimental work as possible. The experience of wiring circuits and taking measurements is a necessary part of the learning process. It will give the student a "feel" for the behavior of d.c. circuits and help him remember facts he needs to know to carry out the necessary computational work.

Experimental activity is considered important also as a means of providing motivation. To keep student interest high, each new topic is introduced by way of an experiment with a discussion following the experiment, and not the other way around.

The goals of this module can be summarized as follows: the student should:

1. Learn the basic physical principles associated with d.c. circuits. In particular, the student should understand the principle of the voltage divider, the fundamental relation known as Ohm's law and how it is applied, the use of series and parallel resistances in voltmeters and ammeters respectively, and the concept of equivalent resistance to simplify a circuit for computational purposes.
2. Understand the operation of a multimeter; in particular, how it works, how it is used to measure voltage, current, and resistance, and how it may alter circuit conditions through loading.

II PREREQUISITES

Since this is an elementary module, no special prerequisites beyond high school algebra are needed. There are, however, a number of terms which appear frequently in electricity, but may not be known to the student. A description of these terms has been included in the introductory part of the module for reference.

III TABLE OF CONTENTS OF THE MODULE

Section A

Introduction
Glossary of Terms and Symbols
The Multimeter
Experiment A-1--Circuits
Experiment A-2--Using the Multimeter
Summary
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Section B

Experiment B-1--The Voltage Divider
Experiment B-2--Ohm's Law
Experiment B-3--Resistance in Series
Experiment B-4--Resistances in Parallel
Applications of Ohm's Law
Kirchoff's Laws
Experiment B-5--Non-Linear Behavior
Summary
Problems

Section C

Experiment C-1--Ammeter Shunt
Experiment C-2--Voltmeter Series Resistance or Multiplier
Experiment C-3--Meter Loading
Summary
Problems

Appendix: Resistor Color Code

IV LEARNING OBJECTIVES

Section A

1. Define the following:
   (a) Multimeter.
   (b) Circuit.
   (c) Short Circuit.
   (d) Open Circuit.
   (e) Series Connection
   (f) Parallel Connection.
2. Name the important parts of a meter movement and describe how the movement works.
3. Describe how an ammeter can be converted into a voltmeter.
4. Describe how the range of a voltmeter can be increased.
5. Describe how the range of an ammeter can be increased.
6. Given a circuit diagram (containing resistors, meters, switches, and power supplies) and the corresponding components, wire the circuit.
7. Given a pre-wired circuit containing resistors, meters, switches, and power supplies, draw the circuit diagram.
8. Use a conventional multimeter to measure an A.C. voltage, a D.C. voltage, a D.C. circuit, or a resistance in a specified part of a circuit.
9. State what is meant by "the meter loads the circuit".
10. State whether a good voltmeter should have a high resistance or a low resistance. Do the same for a good ammeter.

Section B

11. Define the following:
    (a) Voltage Divider.
    (b) Potentiometer.
    (c) Rheostat.
    (d) Linear or Ohmic Device.
    (e) Non-Linear or Non-Ohmic Device.
    (f) Branch Current.
12. Describe with the aid of a diagram how a rheostat or potentiometer is used in each of the following applications: (a) ohmmeter zero adjustment, (b) voltage measurement by balancing a known voltage against an unknown voltage, (c) linear motion potentiometer control and (d) liquid-level sensor.
13. For a uniform wire carrying a constant current, state how the voltage drop depends on the length of wire.
14. Design a voltage divider, consisting of two resistors, which will provide a specified output voltage from a given input voltage.
15. Given a set of known resistors connected in series with a known voltage source, determine the voltage drop across any specified resistor.
16. State Ohm's law.
17. Given two of the following three quantities, calculate the third: the resistance of a circuit component, the current in the component, the voltage drop across the component.
18. For several known resistances connected in series, calculate the equivalent resistance.
19. For several known resistances connected in parallel, calculate the equivalent resistance.
20. List at least three devices which do not follow Ohm's law.
21. Given graphical information on voltage vs. current for a device, determine whether it is ohmic or nonohmic. If ohmic, determine the resistance.

Section C

22. Define the following:
    (a) Ammeter Shunt Resistor.
    (b) Voltmeter Multiplier Resistor.
    (c) Voltmeter Sensitivity Rating.
23. Given the internal resistance, R_M, of a meter movement, and the current, I_M, required to produce full-scale deflection of the meter movement, calculate the required value of the shunt resistor to produce a meter which will have full-scale deflection with a current I. The appropriate equation is

$$R_P = \frac{R_M}{\frac{I}{I_M} - 1}$$

24. Given the internal resistance, R_M, of a meter movement and the current, I_M, required to produce full-scale deflection, calculate the required value of the multiplier resistor, R_S, to produce a meter which will have full-scale deflection with a voltage V. The appropriate equation is

$$R_S = \frac{V}{I_M} - R_M$$

25. Given two of the following three quantities, determine the third: the sensitivity rating for a voltmeter, the maximum voltage on the range in use, the internal resistance for the range in use.
26. Given one of the following, calculate the other: the sensitivity rating for a voltmeter, the current required to produce full-scale deflection of the meter movement.

V LABORATORY ACTIVITIES

Estimated Time for Lab Experiments.

The experiments are approximately of equal length. On the average, students require 35 minutes to complete the procedure part of an experiment. This includes wiring the circuit, taking the measurements, and recording the data. Experiment A-1 may take less time, about 20 minutes. There is almost no wiring involved, because the circuits are already set up for the students. The estimated time for completing all ten experiments is 5 hrs 35 min.

Any of the experiments can be done as a demonstration. If the instructor finds he is limited in laboratory time, he should consider this alternative before deciding to omit an experiment.

Experiment A-1.

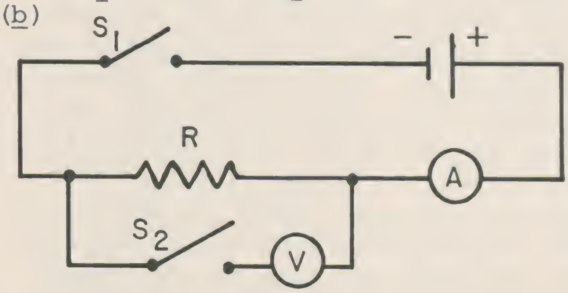
The purpose of this experiment is to introduce the student to the basics of circuits. He will learn how to read and draw circuit diagrams, and make measurements with ammeters and voltmeters. At this stage, he will not be required to do any calculations.

A good way of conducting the experiment is to have the instructor set up all four circuits as described in parts 1, 2, 3, and 4 before the laboratory session begins. During the session, students will be cycled through four stations, working with a different circuit at each station. After completing measurements at one station, they proceed to the next until they have completed measurements at all four stations.

Sample Data:

(a) S_2 open: I = 280 μA
S_2 closed: I = 100 μA
R_1 = 20 kΩ, R_2 = 180Ω

(b)



S_2 open: I = 195 μA
S_2 closed: I = 490 μA
V = 5.8 V
R = 30 kΩ

(c) S_2 open: V = 2.8 V
S_2 closed: V = 6 V
R_1 = 1KΩ, R_2 = 20kΩ

(d) V = 6 V
I = 6 μA
R_1 = kΩ, R_2 = 1MΩ

Experiment A-2.

The a.c. receptacles referred to in part (a) of this experiment are wired as shown:

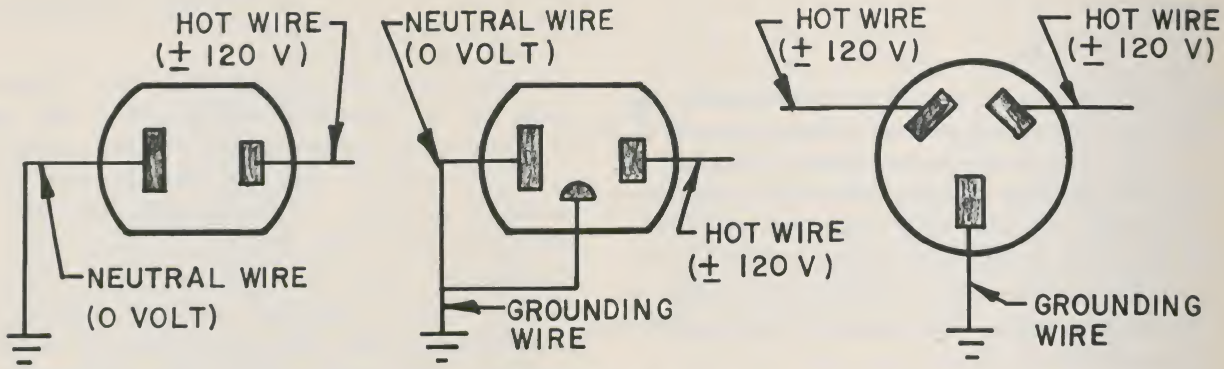


FIGURE 1.

The grounding wire is a safety precaution. If the matching three-prong plug of an electric motor or appliance is inserted in the receptacle, the frame or housing of the motor or appliance will be connected to ground by the grounding wire. This greatly reduces the danger of receiving a shock. For example, if the motor of a hand-drill is defective, the motor winding which is the hot side may touch the motor frame. The operator who holds the tool in his hand will be safe if the frame is grounded, because the current will flow to ground through the grounding wire and not through the operator's body.

Experiment A-2 deals exclusively with practical applications of the multimeter. Depending on student interest, the instructor may wish to expand this activity by including more applications. If you are looking for ideas, here are some you may develop into worthwhile projects.

(1) <u>Test for Poor Conductivity Between Cable and Terminal Post of a Car Battery</u>.

Poor conductivity is caused by chemical corrosion. To perform the test, use the multimeter as a voltmeter and connect as shown in Figure 2.

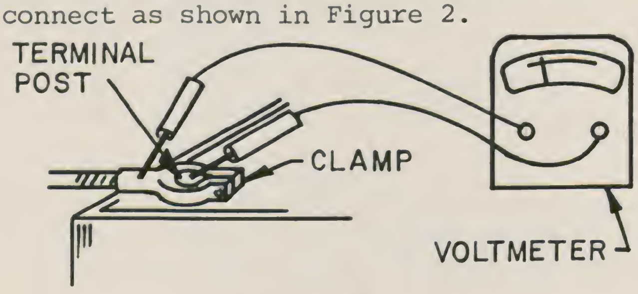


Figure 2.

As the car is started there should be no indication of a voltage drop if the connection is good. Do the same at the other clamp and terminal post. If the voltmeter shows a reading of several volts, the connection is poor and needs cleaning.

(2) <u>Current Drain from a Transistor Radio Battery</u>.

Use the multimeter as an ammeter. Current drain is measured by connecting the ammeter in series with the battery while operating. To check current drain in a transistor radio, disconnect one of the connector terminals on top of the battery and hook up the ammeter as shown in Figure 3. Increase the volume control of the radio and observe the effect on the ammeter.

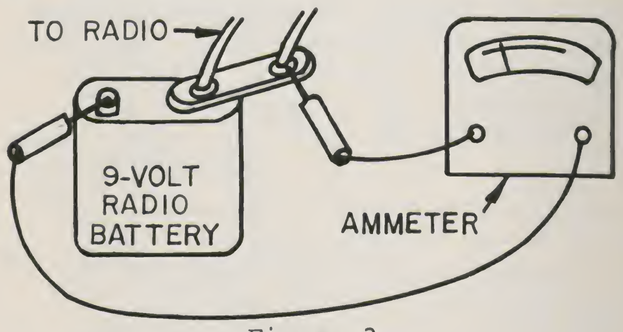


Figure 3.

(3) <u>Conductivity of Solutions</u>.

Fill a small dish or beaker with tap water. Use the multimeter as an ohmmeter (ohmmeter function) and connect as shown in Figure 4.

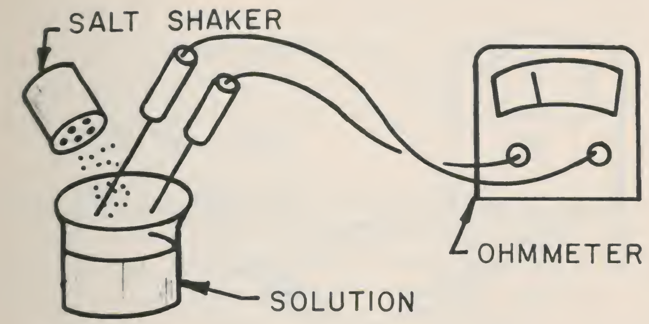


Figure 4.

Typical readings for tap water are 20,000 to 30,000 Ω. Observe the ohmmeter deflection as table salt is added a little at a time. The resistance is very sensitive to salt concentration and decreases quite rapidly until the solution is saturated. At this point the resistance is about 5,000 ohms and remains constant. Students can obtain data to plot a graph of resistance vs. salt concentration similar to the one shown in Figure 5. (A word of caution: do not use flammable liquids for such an experiment.)

(4) Continuity Tests.

To check a wire or circuit component for continuity, use the multimeter as an ohmmeter. Be sure power is turned off and resistor is isolated.

(a) To check if a light bulb is good, connect the ohmmeter across the light bulb. Any resistance reading below infinite is an indication that the filament is "continuous" and the bulb is good.

(b) The same procedure is used to check the continuity of a coil of wire such as a motor winding.

(c) To identify a wire in a strand of many wires, connect one probe of the ohmmeter to the wire at one end of the strand. Touch the other probe to the wires at the other end of the strand, one at a time, until you find the wire which gives a reading below infinite.

(5) Simple Test for Defective Capacitors.

First make sure the capacitor is discharged by shorting its leads. Set the

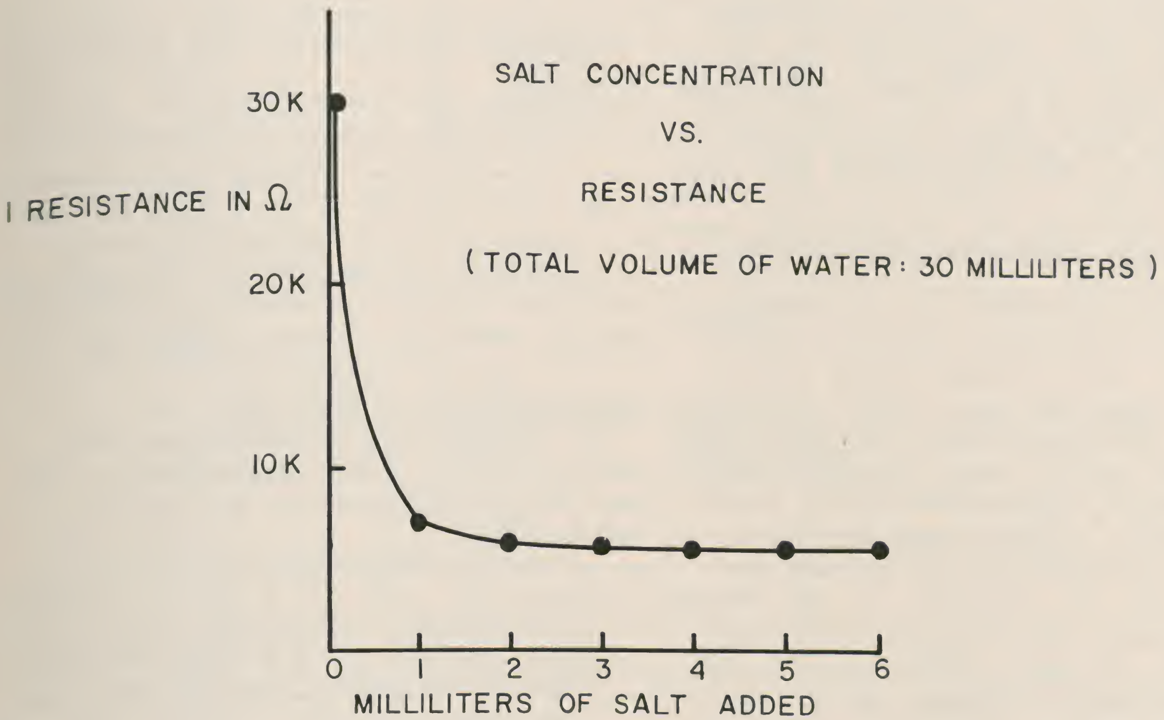


Figure 5

multimeter to the highest resistance scale and connect test leads across the capacitor. If the meter deflects momentarily toward zero resistance as the capacitor charges, and then drifts back toward the high-resistance end as the charging process reaches saturation, the capacitor is behaving normally. If the meter shows zero resistance, the capacitor has a short in it and must be replaced.

(6) Turns Ratio of a Transformer.
The setup is shown in Figure 6.

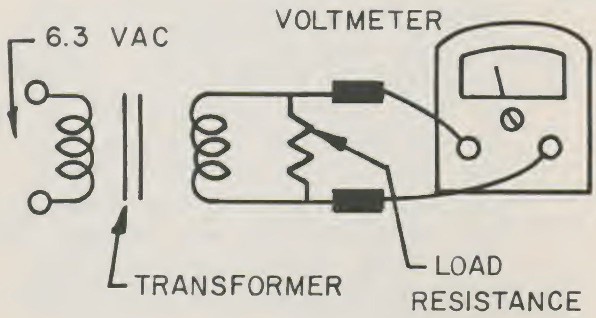


Figure 6.

Apply a comparatively low a.c. voltage to one winding, such as 6.3 a.c. volts from a filament heater power supply, and measure the a.c. voltage produced across the other winding with the multimeter set at a.c. function. The turns ratio is given by $V_1 : V_2$. If the voltage across the second winding reads 63 a.c. volts, the turns ratio would be 1 : 10.

(7) Test for Defective Semiconductor Diodes.
Using the multimeter as an ohmmeter, measure the resistance across a diode both ways. For a normal diode the resistance going one way should be greater than the resistance going the other way by a large factor (many thousand times). The number is referred to as the front-to-back ratio and may vary depending on the type of diode and the voltage applied across it. However, if the resistance is zero, the diode is definitely defective. It has a short circuit and must be replaced. (Note: Do not use a low-sensitivity meter on diodes which cannot stand a modest forward current.

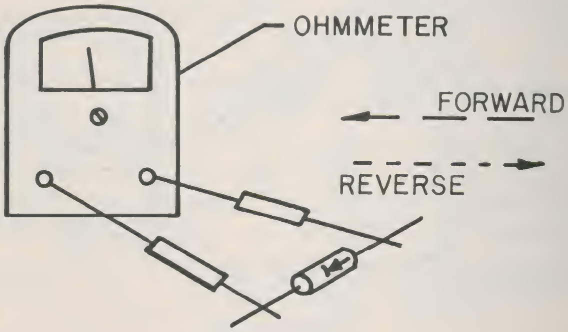


Figure 7.

Experiment B-1: The Voltage Divider.
The nichrome wire serves as a voltage divider. Nichrome was chosen because of its high resistivity (110 x 10^{-8} ohm/m). Thus, reasonable resistance values can be obtained using relatively short lengths of wire. The measurements shown in the table were made with nichrome wire having a resistance of 5.37 ohms/m. That way less wire is needed to do the experiment.

Sample Data:

length ac 10^{-2} m	0	10	20	30	40	50	60	70	80	90	100
voltmeter reading 10^{-2} volt	0	5	9.8	14.8	19.5	24.4	29.4	34.2	39.2	44.1	48.8

Ammeter reading: 148 mA (constant).

Experiment B-2: Ohm's Law.
The voltage and current values are measured for a fixed resistance R. The data below correspond to R = 100 Ω.

Sample Data:

voltage (V)	0.5	1.0	1.5	2.0
current (mA)	4.4	9.2	14.1	19.0

(V)	2.5	3.0	3.5	4.0	4.5	5.0
(mA)	23.9	29.0	34.0	39.0	44.1	49.0

Experiment B-3: Resistances in Series

The data given below were obtained by adjusting the pot to a fixed current of 3 m flowing through the series resistances $\underline{R}_1 = 500\Omega$ and $\underline{R}_2 = 1000\Omega$.

Voltage Measurements:

Step 2. $\underline{V}_{ab} = 1.43$ volts
$\underline{V}_{bc} = 2.86$ volts

$\underline{V}_{ac} = 4.3$ volts; $\underline{V}_{ab} + \underline{V}_{bc} = 4.29$ volts

Conclusion: $\underline{V}_{ac} = \underline{V}_{ab}$, within experimental error.

Step 3. $\underline{V}_{ed} = 0.1$ volt

Conclusion: voltage drop across ammeter is negligible.

$\underline{V}_{ad} = 4.4$ volts, thus, $\underline{V}_{ad} = \underline{V}_{ac}$.

Step 4. $\underline{I} = 3$ mA.

Step 6. The resistors $\underline{R}_1$ and $\underline{R}_2$ are replaced by a single resistor of value 1500Ω. Then $\underline{V}_{ac} = 4.3$ volts, same as before.

Experiment B-4: Resistances in Parallel

Step 2. The pot was set for a constant total current $\underline{I} = 15$ mA. $\underline{V}_{ab} = 4.9$ V.

Step 3. $\underline{I}_1 = 9.8$ mA
$\underline{I}_2 = 5.0$ mA

$\underline{I}_1 + \underline{I}_2 = 14.8$ mA

Conclusion: $\underline{I}_1 + \underline{I}_2 = \underline{I}$, within experimental error.

Step 4. Applying Ohm's law:

$$\underline{I}_1 = \frac{4.9 \text{ volts}}{500 \text{ ohms}} = 9.8 \text{ mA}$$

$$\underline{I}_2 = \frac{4.9 \text{ volts}}{1000 \text{ ohms}} = 4.9 \text{ mA}$$

$$\underline{I}_1 + \underline{I}_2 = \qquad = 14.7 \text{ mA}$$

Step 5. $\underline{R} = \frac{\underline{V}}{\underline{I}} = \frac{4.9 \text{ volts}}{15 \text{ mA}} = 327\ \Omega.$

Step 6. $\underline{R}_1$ and $\underline{R}_2$ are replaced by a single resistor $\underline{R} = 332$ ohms. In this case, the measured values of voltage $\underline{V}_{ab}$ and current $\underline{I}$ are 4.88 volts and 15 mA, respectively. Agreement with values measured in Step 2 is good.

Experiment B-5: Non-Linear Behavior

Sample Data: a 6-volt, #428 miniature lamp.

VOLTAGE (V)	0.2	0.5	1.0	1.5	2.0	2.5
CURRENT (mA)	36	54	71	86	99	111

(V)	3.0	3.5	4.0	4.5	5.0
(mA)	122	133	142	152	162

Experiments C-1 and C-2: Ammeter Shunt and Voltmeter Multiplier

The internal resistance of the meters must be known in order to be able to compute shunt and multiplier resistances. The meters supplied by Thornton Associates have an internal resistance of $1k\Omega$ (max. deflection at 100 μA).

Experiments C-1 and C-2 can be performed in an alternate way using one instead of two meters. The current in the circuit is determined by using Ohm's law, $\underline{I} = \frac{\underline{V}}{\underline{R}}$, where $\underline{V}$ is a known voltage source and $\underline{R}$ is a known resistor. However, the results obtained in this way may not be as accurate. They will depend very much on the tolerance of the resistor. For this reason, it is better to follow the procedure described in the module.

Experiment C-3: Meter Loading

Sample Data:

	VHI connected across $\underline{R}_1 + \underline{R}_2$	VHI connected across $\underline{R}_1$
VHI (V)	5.8	2.9
I (mA)	.279	.270
VLO (V)	not connected	not connected

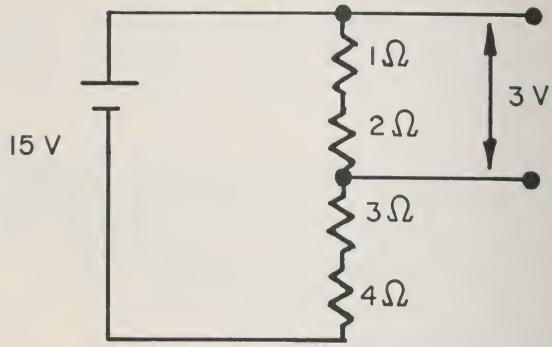
	No Voltmeters connected	VLO connected across $\underline{R}_1$
VHI (V)	not connected	not connected
I (mA)	.269	.321
VLO (V)	not connected	2.2

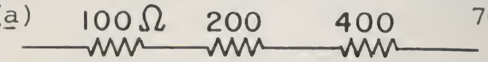
VI ANSWERS TO PROBLEMS

Section A

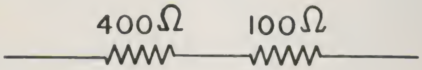
1. Left Column — Right Column
   - 1 — c
   - 2 — d
   - 3 — a
   - 4 — b
2. Low range — 10kΩ
   Medium range — 100kΩ
   High range — 1MΩ
3. (a) 1Ω
   (b) 10,000Ω
4. (a) yes
   (b) no
   (c) The additional resistor placed in series with the ammeter will reduce the current in the circuit. To increase the range of the ammeter, the resistor must be placed in parallel.
5. (a) Yes, if the resistor in parallel short-circuits the meter.
   (b) no
   (c) To increase the range of the voltmeter, he must add a resistor in series with the meter.

Section B

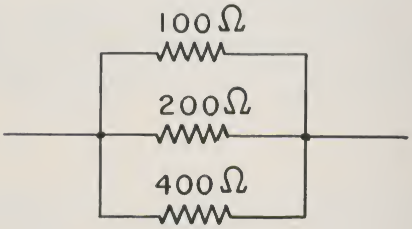
1. 

2. V_{ab} = 0.8 V
   V_{ac} = 2.4 V
   V_{ad} = 5.6 V
3. Equivalent resistance is 46.1 ohm.
4. (a) 

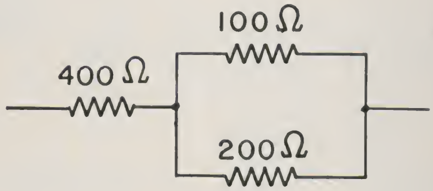
   700Ω

   (b) 

   500Ω

   (c) 

   57Ω

   (d) 

   467Ω

5. (a) 1 A
   (b) 4 A
6. (a) current in the 10-Ω resistor is 0.4 A
   current in the 20-Ω resistor is 0.3 A
   current in the 60-Ω resistor is 0.1 A
   (b) 4 V
7. "a" is ohmic. Its resistance is $\frac{\Delta V}{\Delta I} = \frac{10V}{4A} = 2.5\Omega$.

Section C

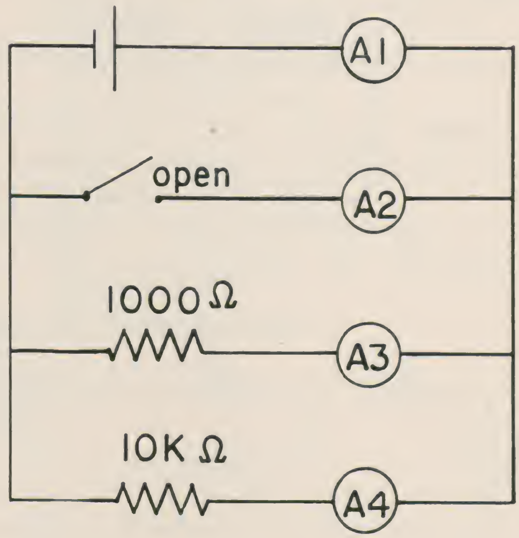
1. (a) 25Ω
   (b) 0.02Ω
2. 100kΩ
3. 5,000 ohm-per-volt
4. 2MΩ
5. 25 μA
6. (a) ammeter reading: 0.15 mA
   voltmeter reading: 0.97 V
   (b) ammeter reading: 0.098 mA
   voltmeter reading: 1 V

VII Post-Tests

#1 Section A

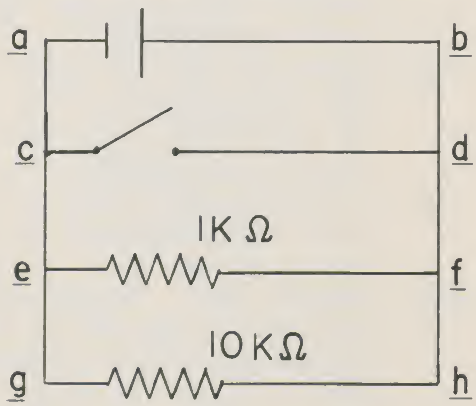
1. (a) A circuit is to be set up consisting of a power supply and three resistances R_1, R_2, and R_3, in series. An ammeter is to be included to measure the circuit current, and a voltmeter to measure the voltage across the resistor R_2. Draw the circuit diagram with the meters and label all components.
   (b) It is found that the voltmeter deflects off scale. How can this be remedied?
   (c) The circuit is changed by placing R_1 in parallel with R_2. A knife switch is added so that R_3 will be short-circuited if the switch is closed. The meters are left in place. Redraw the diagram.
   (d) When R_1 is in parallel with R_2, it is found that the ammeter deflects off scale. How can this be remedied?
2. (a) Name the important components of a meter movement and describe how the movement works.
   (b) Is the meter movement basically an ammeter, a voltmeter, or an ohmmeter?
   (c) How do you check the voltage of a battery using a multimeter? Draw a circuit diagram showing the connections and describe the symptoms of a run-down battery as opposed to the behavior of a good battery.
   (d) For a circuit consisting of a d.c. voltage source and a resistance, how do you measure its current using a multimeter? Show in terms of a circuit diagram.
3. (a) What are the two basic rules for measuring the resistance of a resistor which is connected in a circuit?
   (b) A technician wishes to measure the resistance of a resistor known to be at least 10,000 ohms. He has at his disposal a multimeter with resistance scales marked R x 1 ohms and R x 100 ohms. Assume the resistor is not connected in a circuit. Describe the operations involved and the scale he should use in making the measurement.
4. (a) Four identical ammeters are connected as shown. List them in the order of decreasing deflection:

most deflection ____
____
____
least deflection ____



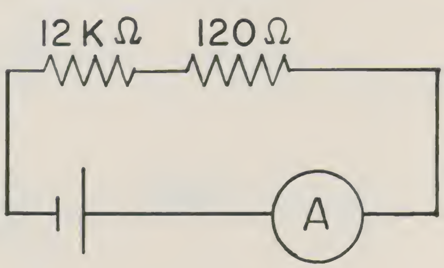
(b) The ammeters are removed and converted into voltmeters. How are ammeters converted into voltmeters?

(c) The voltmeters are used to measure the voltage drops across the circuit points ab, cd, ef, and gh. Indicate in the diagram how the voltmeters must be connected.



(d) Do you expect some or all of the voltage readings to be equal or different? Explain.

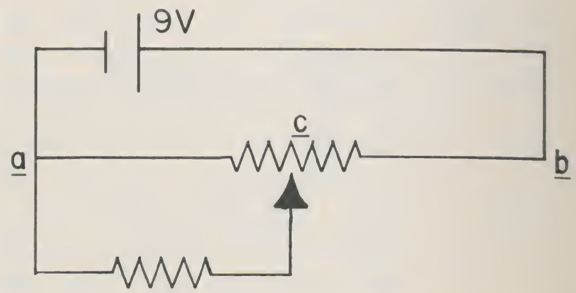
5. A voltmeter having an internal resistance of 10 kΩ, is used to measure voltage drops in the circuit shown. Discuss the effect on the reading of the ammeter A, if the voltmeter is connected across the (i) 12-kΩ resistor, (ii) 120-ohm resistor. Give reasons.



Section B

6. Draw a circuit diagram in which three resistors having the values 300, 600, and 900 ohms are connected in series across a 24-volt d.c. voltage source. If they are used as a voltage divider, indicate the tap which will provide 12 volts with respect to the negative terminal of the voltage source.

7. The segment ab is a uniform wire 10 meters long and serves as the resistance of a potentiometer. The slider is set so that the resistance R_{cb} is 600 ohms and the voltage drop across it is 4 volts.



(a) What is the resistance R_{ac}?

(b) What is the length of wire (in meters) contained in the resistance R_{ac}?

8. Show with diagrams how a rheostat is:

(a) connected in the basic ohmmeter circuit;

(b) used as part of a liquid-level sensing device.

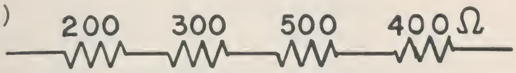
9. For the circuit shown:

(a) Find the current which is indicated by the ammeter A.

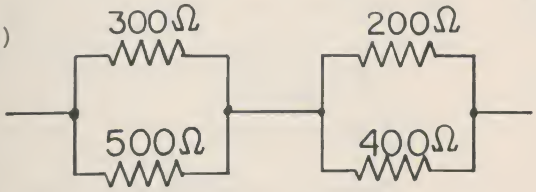
(b) What are the voltages which are measured by a voltmeter across the points ab and bc?

10. Find the equivalent resistance of the following combinations of resistors:

(a)



(b)



11. A silicon diode is found to have the following sets of voltage and current values:

Voltage V (volts)	-0.1	0	0.2	0.4	0.6
Current I (mA)	0	0	0.3	0.6	1.0

V	0.8	1.0
I	3.0	6.0

(a) Plot its characteristic curve, I in mA along the vertical, V in volts along the horizontal axis.

(b) Is the device ohmic or non-ohmic over the range from -0.1 volt to 1.0 volt?

(c) From the slope of the graph determine the diode's resistance in ohms at 0.3 volt and at 0.9 volt.

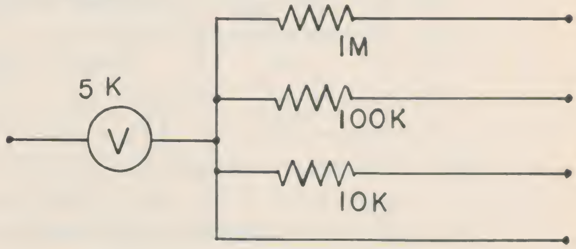
Section C

12. An ammeter movement has a resistance of 4kΩ. It deflects full-scale when 0.2 volt is applied across its terminals.

(a) What is the current in mA at full-scale deflection?

(b) Calculate the shunt resistance needed to increase the range of the ammeter ten times.

13. A voltmeter with an internal resistance of 5kΩ can be connected in series with each of three resistors having the values 10kΩ, 100kΩ, and 1MΩ for the purpose of changing the meter's range. What is the factor n by which its range is changed in each case?

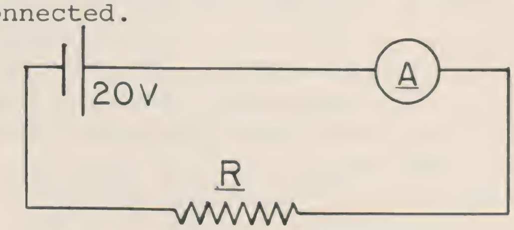


14. A voltmeter has a sensitivity rating of 20,000 ohms per volt.

(a) If it is used on a 0-150 volt range, what will be its internal resistance?

(b) What current in μA must flow through the meter itself to produce full-scale deflection?

15. The voltage source in the circuit shown provides a constant voltage of 20 volts. The ammeter A, which has negligible internal resistance, reads 0.4 mA before a voltmeter is connected.



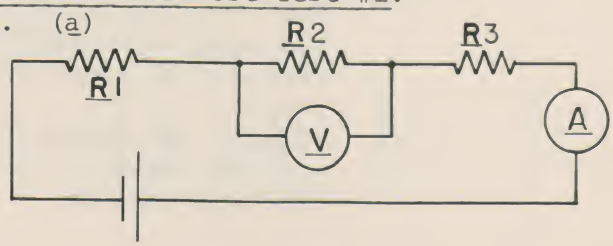
(a) What will be ammeter and voltmeter readings if a 1,000 ohms-per-volt voltmeter on a 30-volt range is connected across the resistance R?

(b) Calculate the percent change in the ammeter reading due to voltmeter loading.

(c) What is the voltage drop across R without the voltmeter connected?

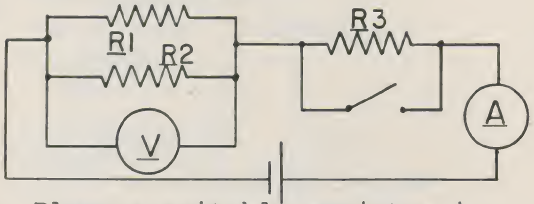
Solutions for Post-Test #1.

1. (a)



(b) Place a suitable resistor in series with the voltmeter. This increases the range of the voltmeter.

(c)

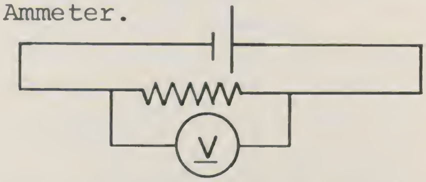


(d) Place a suitable resistor in parallel with the ammeter. This increases the range of the ammeter.

2. (a) Moving coil, permanent magnet, pointer, scale plate, restoring spring. Current in moving coil interacts with magnetic field of permanent magnet causing coil to rotate and pointer to deflect.

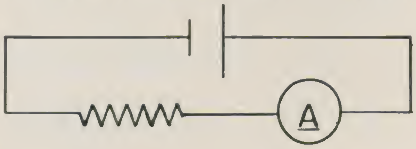
(b) Ammeter.

(c)



Symptom of run-down battery: Voltmeter reading gradually decreases. Sign of good battery: Voltmeter reading at rated value and steady.

(d)



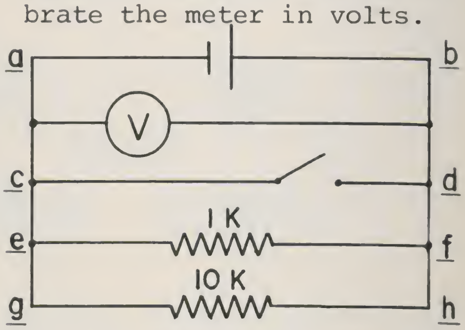
3. (a) (i) Turn the power off.
(ii) Isolate (disconnect) the resistor.

(b) (i) Switch multimeter to OHMS function.
(ii) Select high enough ohms scale: R x 100 ohms.
(iii) Calibrate with zero-ohms control, probe tips touching. When the instrument reads zero, it is ready for use.
(iv) Connect the probes to ends of resistor and take measurement.

4. (a) Most deflection A1
A3
A4
Least deflection A2

(b) Connect a resistance in series with the ammeter and recalibrate the meter in volts.

(c)

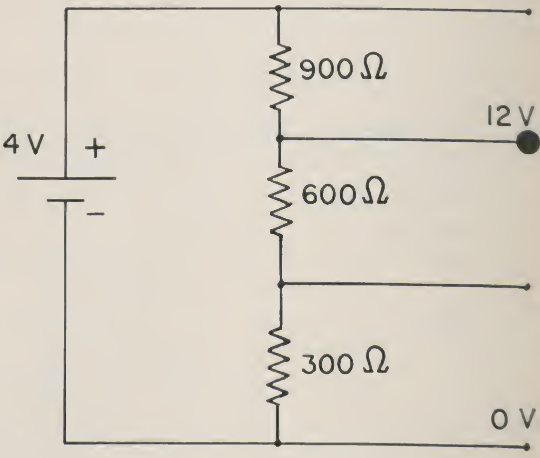


(d) The voltage readings are equal because points a, c, e, and g can be considered as a single point and points b, d, f, and h as another single point. The voltage across the two points can have only one value.

5. If the voltmeter is connected across the 12kΩ resistor, loading is significant because the voltmeter's internal resistance is comparable to 12kΩ. Ammeter reading will increase noticeably.
If the voltmeter is connected across the 120Ω resistor, loading is not important because the voltmeter's internal resistance is much greater than 120Ω. Ammeter reading will not change very much.

Section B

6.



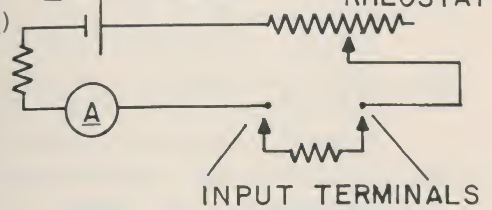
7. (a) $\frac{4V}{600\Omega} = \frac{5V}{x\Omega}$, $x = 750\Omega$

(b) $750\Omega + 600\Omega = 1350\Omega$

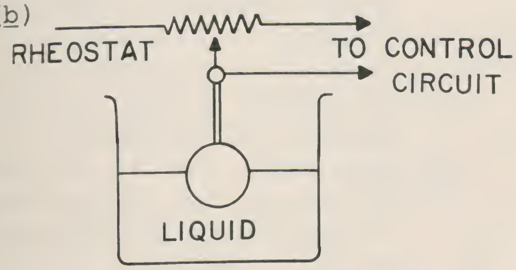
$\frac{x \text{ meter}}{750\Omega} = \frac{10 \text{ meter}}{1350\Omega}$;

$x = 5.5$ meter

8. (a)



(b)



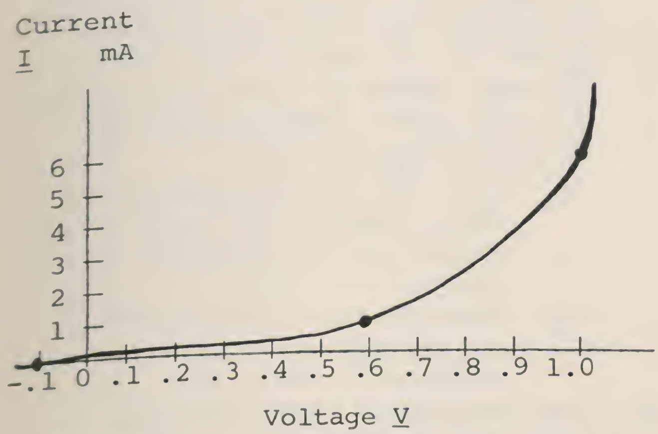
9. (a) 86 mA

(b) V_{ab} = 10.3 volts; V_{bc} = 4.7 volts.

10. (a) 1400Ω

(b) 321Ω

11. (a)



(b) non-ohmic

(c) at 0.3 volt, $R = \frac{\Delta V}{\Delta I} = \frac{0.2\ V}{0.3mA}$

= 667 ohms

at 0.9 volt, $R = \frac{\Delta V}{\Delta I} = \frac{0.2\ V}{3\ mA}$

= 66.7 ohms

Section C

12. (a) 0.05 mA

(b) 444 ohms

13. (a) 3

(b) 21

(c) 201

14. (a) 3MΩ

(b) 50μA

15. (a) Ammeter reading 1.067 mA. Voltmeter reading 20 volts.

(b) 167%

(c) 20 volts

#2

Section A

1. (a) What causes the pointer of a meter movement to deflect?

(b) Name the three electrical quantities which can be measured with a multimeter.

(c) What is the advantage of providing a multimeter with more than one range?

2. You are given a circuit consisting of a battery and three identical resistors, two of which are connected in parallel; the third is connected in series with the parallel combination. You are also supplied ammeters and voltmeters for measuring currents and voltages in the circuit.

(a) Draw the circuit diagram showing how an ammeter A and a voltmeter V must be connected if you wish to measure the current in one of the branches of the parallel combination, and the voltage across it.

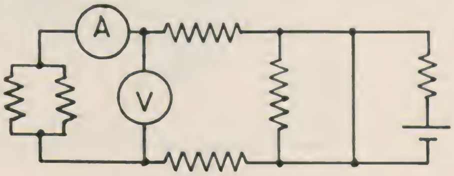
(b) Indicate the polarity of the battery and of the meters with positive and negative signs.

3. Each of the four circuit diagrams shows one of the following:

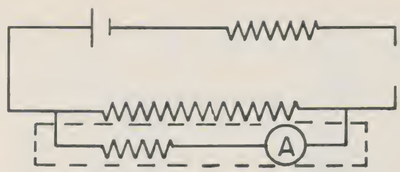
(i) shunt resistance
(ii) multiplier resistance
(iii) short-circuit
(iv) an ammeter converted to a voltmeter

Match diagrams a, b, c, and d with the items i, ii, iii, and iv.

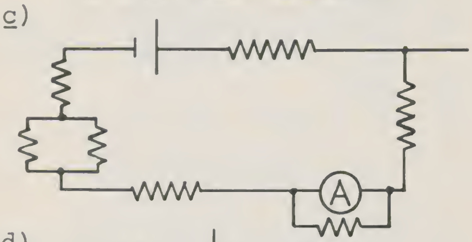
(a)



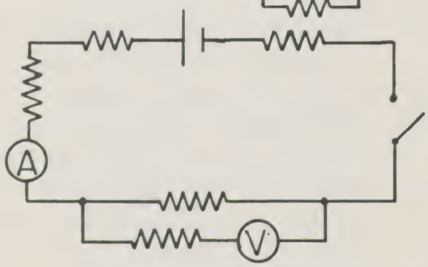
(b)



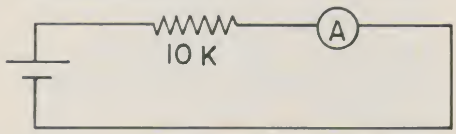
(c)

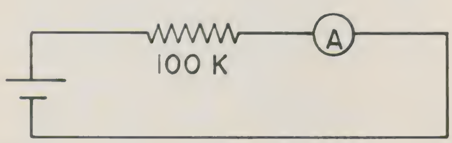


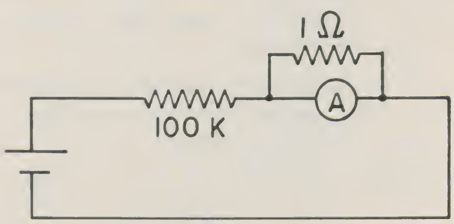
(d)



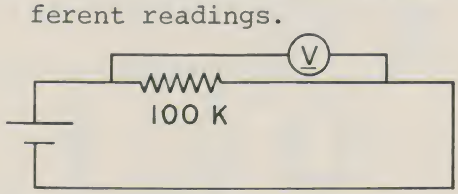
4. (a) Assume the batteries and ammeters shown in all three diagrams are identical. Explain why meter readings are different.

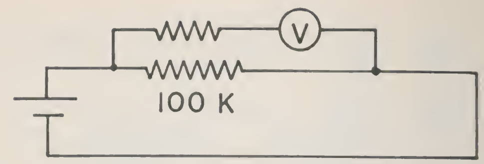






(b) Assume the batteries and voltmeters V in the two diagrams are identical. Explain why the voltmeters show different readings.





(c) Which is better, a voltmeter having a high or a low resistance? For what reason?

(d) Which is better, an ammeter having a high or low resistance? For what reason?

5. (a) Describe how you proceed measuring a.c. line voltages up to 240 volts using a multimeter.

(b) How do you determine with a multimeter whether or not a battery is run down?

(c) What steps must be followed to measure the resistance of a resistor which is connected in a circuit?

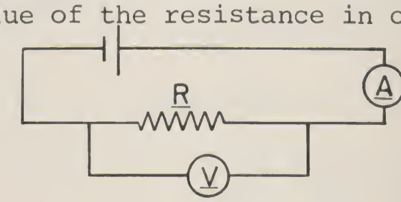
Section B

6. A wire which has a length of 36 meters and a resistance of 6 ohms per meter, is used as the resistive element of a voltage divider. If a voltage of 3 volts is applied across it, at what point must the wire be tapped to provide a voltage of 0.75 volt? State your answer in meters and in ohms.

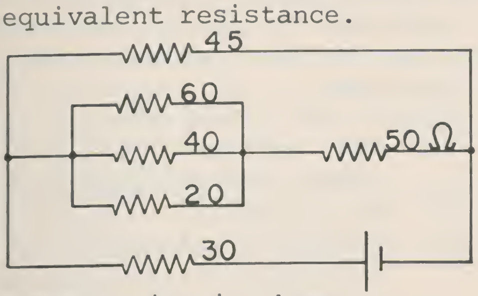
7. (a) Draw the circuit diagram of a basic ohmmeter and explain the purpose of the rheostat in the circuit.

(b) Describe how a potentiometer can be used to measure unknown voltages.

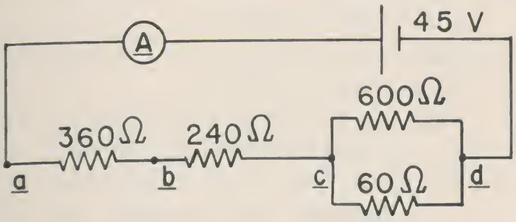
8. The resistance R of a resistor is measured by the ammeter-voltmeter method as shown in the accompanying diagram. The following readings were obtained: Current I = 4mA, voltage V = 12 volts. Compute the value of the resistance in ohms.



9. For the given circuit find the equivalent resistance.



10. For the circuit shown:
(a) compute the current as measured by the ammeter A.
(b) What are the voltages as measured by a voltmeter across the points ab, bc, cd, and ad?



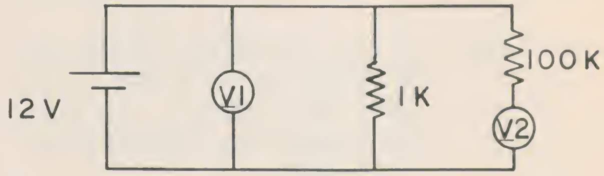
11. The following current and voltage measurements were obtained for a special type of semi-conducting diode (tunnel diode):

Voltage (volts)	-0.05	0	0.1	0.2	0.4	0.5	0.6
Current (mA)	-2.0	0	3.5	1.5	0.5	1.0	4.0

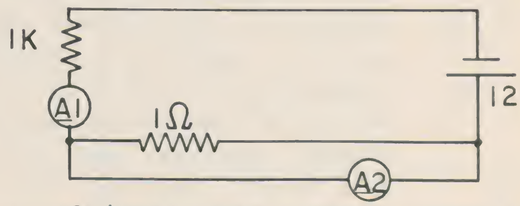
(a) Plot the diode's characteristic curve.
(b) From your graph determine the voltage values which can produce a current of 2 mA in the device.
(c) What happens to the current as the voltage is increased (i) from 0 to 0.1 volt, (ii) from 0.1 to 0.2 volt?
(d) For the range you have plotted, is the device ohmic or non-ohmic?

Section C

12. Two identical voltmeters V1 and V2, each having an internal resistance of 50 kΩ are connected in a circuit as shown. What is the voltage each meter reads?



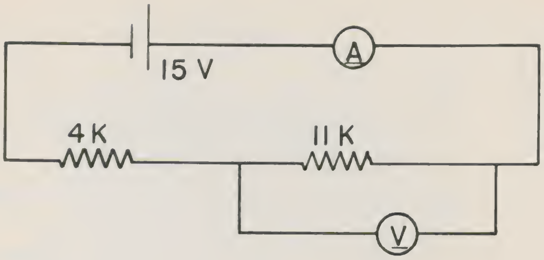
13. Two identical ammeters A1 and A2, each having an internal resistance of 5 ohms, are connected in a circuit as shown. What is the current each meter reads?



14. A multimeter has a moving coil of internal resistance 6000 ohms and reads 300 μA at full-scale deflection. Beside the 0-300 μA range, the meter has the following additional current ranges: (a) 0-30 mA, and (b) 0-300 mA. Compute (to the nearest ohm) the shunt resistances needed for the additional ranges.

15. (a) A multimeter, when used as a voltmeter, has a sensitivity rating of 10,000 ohms per volt. Compute the current flowing in the meter which will produce full-scale deflection.
(b) The multimeter is equipped with the following d.c. voltage ranges: 0-1.5V and 0-15V. Compute the voltmeter's internal resistance for each of the voltage ranges.

16. A 10,000-ohm-per-volt voltmeter is used to measure the voltage across the 11kΩ resistor shown in the circuit diagram.



(a) If the voltmeter range is switched to 0-1.5V calculate the current (in mA) which will be measured by the ammeter A.

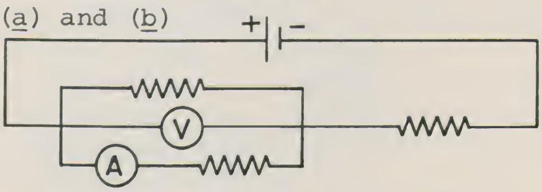
(b) If the voltmeter range is switched to 0-15V, calculate the current (in mA) which will be measured by the ammeter A.

(c) Calculate the current measured by ammeter A if the voltmeter is not connected. Which of the two voltmeter ranges produces more serious meter loading?

Solutions for Post-Test #2.

1. (a) Interaction between the current in the moving coil and the magnetic field of the permanent magnet.
   (b) Voltage, current, and resistance.
   (c) You can measure more values of an electrical quantity more accurately.

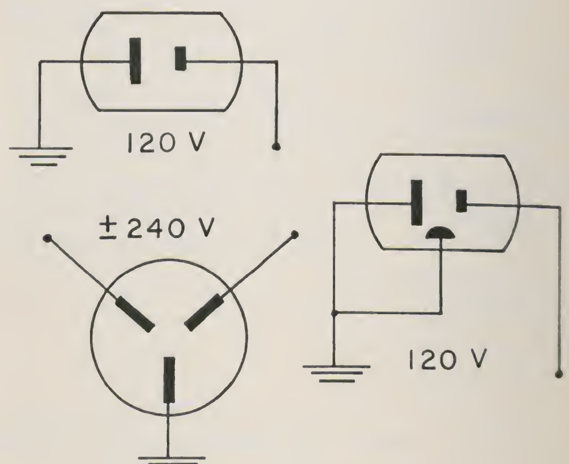
2. (a) and (b)



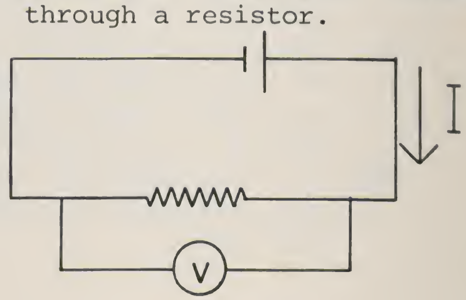
3. (i) (c)
   (ii) (d)
   (iii) (a)
   (iv) (b)

4. In the circuit containing the 10-kΩ resistor, the current is largest, so the ammeter reading is highest. In the circuit containing the 100-kΩ resistor and no shunt, the current is less, so the ammeter reading is less. In the circuit containing the 100-kΩ resistor and shunt, the current is about the same, but most of it by-passes the ammeter through the shunt, so the ammeter reading will be lowest.
   (b) In the first circuit, the entire voltage drop across the 100-kΩ resistor appears across the voltmeter. In the second circuit a multiplier is used. A portion of the voltage drop appears across the multiplier. The voltage across the voltmeter is therefore less, and its reading will be lower than that in the first circuit.
   (c) High resistance. Reason: less loading.
   (d) Low resistance. Reason: less loading.

5. (a) Set the multimeter to the a.c. volts function and select a range of at least 240 volts. Insert multimeter probes in a.c. receptacle. Expected voltages are as shown:



   (b) Measure battery voltage while battery is delivering current through a resistor.

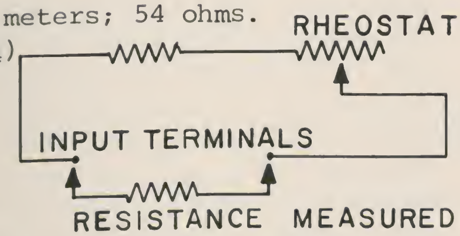


If battery is good, voltmeter reading will show rated value and remain steady. If battery is run down, voltmeter reading will decrease gradually.

(c) step 1. Turn power off.
2. Disconnect the resistor from the circuit.
3. Set multimeter to Resistance function, and select high enough range.
4. Calibrate the meter by connecting probe tips and setting zero-ohms control for zero ohm reading.
5. Connect probe tips to ends of resistor and measure.

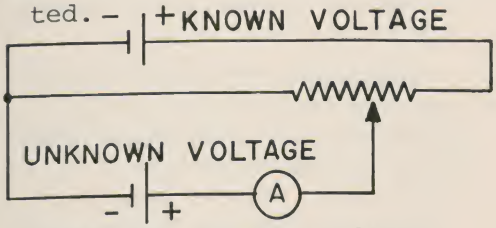
Section B

6. 9 meters; 54 ohms.
7. (a)



The rheostat is used to adjust ohmmeter for zero ohm reading. To do this calibration, the input terminals to the ohmmeter must be shorted.

(b)

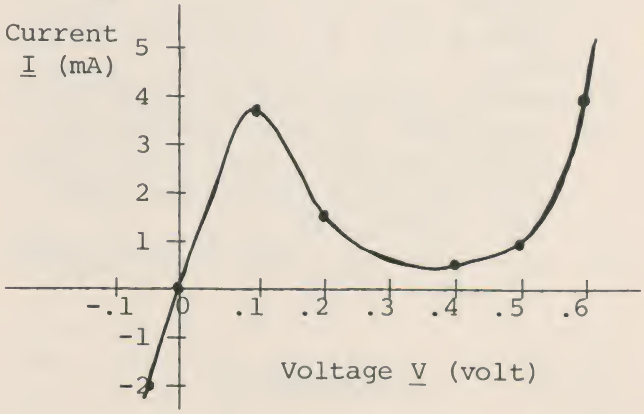


Known and unknown voltage sources are connected with polarities opposing each other. Sliding contact c is adjusted for zero reading of the current meter. This is the balance condition at which the unknown voltage is equal to the known voltage.

8. $\underline{R} = \dfrac{12 \text{ volts}}{4 \text{ mA}} = 3000\Omega$
9. 55.1 ohms
10. (a) 68.8 mA
(b) 24.8 V
16.5 V
3.7 V
45 V

Section C

11. (a)



(b) 0.05 V; 0.17 V; 0.55 V.
(c) (i) current increases;
(ii) current decreases.
(d) non-ohmic.

12. V1 reads 12 volts.
V2 reads 4 volts.
13. A1 reads 12 mA.
A2 reads 2 mA.
14. (a) 60 ohms.
(b) 6 ohms.
15. (a) 100 μA
(b) (i) 15,000Ω
(ii) 150,000Ω
16. (a) 1.45 mA
(b) 1.05 mA
(c) 1 mA. The lower range produces more serious meter loading.

VIII LIST OF APPARATUS

1) Power supply, 0-15 volt d.c. variable, e.g. Thornton Associates Model UPS-100.

2) Microammeters, full-scale at 50μA 200 millivolt.
3) Multimeter, low-sensitivity (1000-ohms-per-volt),e.g. Lafayette 99E50791.
4) Knife-switches.
5) Mounted nichrome wire #24, 1 meter long.
   Plug-in units for microammeters.
   Shunts: 0-500 mA, 0-50 mA, 0-5 mA, 0-0.5 mA.
   Multipliers: 0-15V, 0-5V, 0-0.5V.
6) Lamp #57 (0.24 A, 14 volts) with socket.
7) Lamp (0.3 A, 4 volts) with sockets.
8) Double battery holder for D-cells.
9) Assortment of carbon resistors, nominal values: 100Ω (5W), 500Ω, 1kΩ, 2kΩ, 4kΩ, 8kΩ, 10kΩ, 20kΩ, 80kΩ, 100kΩ, 1MΩ.
10) Assortment of leads, banana plugs, alligator clips.

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Electricity and Magnetism, Duckworth, MacMillan, 1960.

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INSTRUCTOR'S MANUAL FOR PHOTODETECTORS

CONTENTS

I INTRODUCTION

Several kinds of topics are interweaved through the three sections of this module. First are the photodetectors (photovoltaic cell, phototube, photoconductor). Each section focuses on a different detector so that the student gets experience in using a variety of devices. Next are the technical characteristics by which photodetectors are specified. Each section concentrates on one or perhaps two of these characteristics, showing in each case how the characteristic can be measured. Finally, there is the physical behavior on which each detector depends. In some cases the behavior will reveal a law of physics or the nature of some quantity, for example light. In others, a picture or model must be developed, for example the model of conduction in semiconductors.

Section A introduces the *photovoltaic cell*, both silicon and selenium. These are used to measure the relative intensities of a standard candle and a standard incandescent bulb. The students are also shown a simple method of comparing the intensities of two light sources by eye. These experiments are designed to introduce the photometric terms (intensity, flux and illuminance) and their units. The student also measures the decrease in photovoltaic output with distance from a point source. The Inverse Square Law of Radiation is introduced in order to determine the *linearity* and *sensitivity* of the two types of cells from the data. In an optional experiment the student can investigate how photovoltaic cells are used to generate electrical power.

Section B introduces the *phototube*. The student first investigates the way in which light falling on the photocathode releases electrons (the photoelectric effect). He then measures *spectral sensitivity*, first in a qualitative way for his own eye, and then quantitatively for the phototube. To determine the spectral sensitivity curves, the spectral distribution of the light source is given so that the student can correct his data.

The failure of the wave picture to account for the photoelectric effect is then discussed, followed by a development of the particle picture. A rough estimate of the photocathode work function is made from the long wavelength "cutoff" of the spectral sensitivity curve.

Section C introduces the *photoconductor*. Its *response time* is measured using a strobe and an oscilloscope. The *temperature dependence* of the dark current of an ordinary diode is also measured as an example of the thermal behavior of semiconductors. As a final experiment to see how photoconductors are used in control systems, the student builds a simple photoelectric burglar alarm.

To explain the characteristics of the photovoltaic cell and photoconductor, the atomic structure and the conduction process in semiconductors are described in terms of the thermal activation of conducting electron-hole pairs. The limitations of this localized electron picture due to the Heisenburg Uncertainty Principle and the Pauli Exclusion Principle are pointed out, and an energy level picture

is then developed. The photoactivation of electron-hole pairs is given in this energy level picture to explain the photoconductor behavior.

A rough estimate of the energy gap in silicon can be made from the long wavelength cutoff of the silicon photovoltaic spectral sensitivity curve. This is compared to a value calculated from their data of the temperature dependence of the dark current in a diode.

II SPECIAL PREREQUISITES

There are no special prerequisites for this module, except that for the Physics of Technology series as a whole: high school algebra.

III TABLE OF CONTENTS OF THE MODULE

IV GOALS

The objectives of the Photodetectors module have been included at the begining of the module.

V DISCUSSION OF ACTIVITIES

The module is divided into three Sections, each representing approximately one week's study. It assumes that ap-

proximately three class hours and two lab hours will be devoted to each section. A recommended scheduling of class and lab activities, and content of class periods, is as follows:

First Class Period

This should orient the student to the topics that will be covered in the section and to the experiments that will be performed. It should include background material, for example a short film about the topic, and a discussion of the lab experiments and apparatus that will be used.

Laboratory Session

The laboratory experiments should be done before the week's final two class sessions. They generally can be done in a two-hour lab period though slower-working students may take somewhat longer.

Second Class Period

This should discuss the laboratory activities and the data taken. The students should be helped in graphing and analyzing their results and in understanding the behavior in terms of the underlying physical laws or principles. If the optional experiments were not done by the students, they can be done here as demonstrations. Problems and questions can be assigned at this time.

Third Class Period

This should continue the discussion of the physics underlying the device behavior. The assigned Questions and Problems can also be discussed. It is often a good idea to end this class with a short 20-minute quiz on the section's work.

The following are specific notes relating to each section.

SECTION A

Fairly good results can be obtained in Experiment 1 if the student is careful and makes several independent trials until the estimated position is reproducible to within a centimeter. A good dark room and a black, non-reflecting surface and surroundings will also help. The basis for this method may be discussed prior to the lab session so that the students can immediately check their results to see how close they came to the actual intensity ratio. This experiment can also be done as a class demonstration with good effectiveness. It is interesting to also compare the intensities of a fluorescent and an incandescent bulb of the same wattage.

When using a photovoltaic, the students should be cautioned about not touching the surface, since the material is fragile. The optional experiment on using the photovoltaic as a solar cell is particularly interesting to students. Data on local average solar radiation can be obtained from several sources. This can then be used to introduce a discussion of solar power as an energy source for home consumption.

Two good references on this and other photometric and radiometric topics are:

American Institute of Physics Handbook
McGraw-Hill Book Company
New York, New York 10020

RCA Electro-Optics Handbook
RCA Commercial Engineering Division
Harrison, New Jersey 07029

SECTION B

The spectral sensitivity measurement for the eye also yields quite good results if the students are careful. It is particularly important for the students to accurately set the width of the spectrum from 400 to 700 mm, since this establishes their wavelength scale in subsequent analyses. The teacher should check this before letting the student go on. As in Section A this makes a good class demonstration provided that a good quality grating is used to get a bright spectrum. Bausch and Lomb sells one that is specifically

designed for use with a projector in a large classroom. It is available from several sources.

The teacher should also determine if any of the students are color blind. The experiments are somewhat difficult for such students. If color-blind students are present, it is sometimes effective to have them describe to the class what they see from the spectrum.

Almost any vacuum phototube can be used for these experiments. Spectral responses for types other than the 929 can be found in the RCA Handbook. It is important for these experiments that the light source be quite intense and that a relatively good grating be used in order to get the phototube output large enough to measure. The lower the output, the higher the amplifier gain that will be required. The gas phototube gives a somewhat higher output, but the explanation of the enhancement is more complicated, though interesting. The standard experiment using a phototube to determine Planck's constant can also be done as an option. It was not included in the module since the procedure is tedious and the results are generally poor.

The discussion on the spectral distribution of sources is brief and includes only enough to let the students know that their data must be corrected. If the teacher wants to develop this more, the Incandescent Lamp and the Fluorescent Lamp modules provide several good experiments and discussions. The discussion of the wave picture of light is also brief. To supplement this, some of the experiments and discussion of The Spectrophotometer module can be used.

SECTION C

Students find the third experiment in this section, building a burglar alarm, a lot of fun and a rewarding ending to the module. The basic circuit with a relay can be used to photo-automate a wide range of systems, and the teacher may want to have several options available.

The discussion on the conduction process in semiconductors has been greatly simplified, as the knowledgeable reader will note. The true nature of semiconductors is most accurately described in the language and mathematics of quantum mechanics. This, of course, is beyond the level of most students. The more pictorial view presented here is only designed to give the student a mental picture of what is happening in order to give them a plausible basis for understanding semiconductor behavior. We trust that the purists do not object.

The discussion on determining the energy gap by the thermal drift method is particularly brief. A discussion of the physics behind why the slope of log $\underline{I}$ vs $1/\underline{T}$ should be proportional to the energy gap is summarized below for the teacher who would like to give the student the physics basis for the method.

The probability for thermal activation, A, of a conduction electron across the energy gap, Eg, is given by the Boltzmann factor; i.e.,

$$A \propto e^{-Eg/kT}$$

In the steady state at temperature, T, the number of conduction electrons is constant, so that the rate of thermal activation equals the rate of recombination, R; i.e.,

$$A = R$$

The recombination rate can be shown to be proportional to the product of the number of conduction electrons, n, and the number of holes, h; i.e.,

$$R \propto nh$$

In an intrinsic semiconductor, like silicon, n = h so that:

$$R \propto n^2 \propto e^{-Eg/kT}$$

or: $$n \propto e^{-Eg/2kT}$$

The conduction current is, to a first approximation, proportional to n, so that:

$$i \propto e^{-Eg/2kT}$$

or: $$i = i_o e^{-Eg/2kT}$$

Taking the natural log of both sides gives:

$$\ln i = \ln i_o - \frac{Eg}{2kT}$$

or in terms of the common logarithm:

$$\log i = \log i_o - .434\ Eg/2kT$$

or: $$\log i = C - .434\ Eg/2kT$$

which is the equation given in the text.

A good reference on the structure and conduction process in semiconductors is Volume 1 of a series produced by the Semiconductor Electronics Education Committee titled:

<u>Introduction to Semiconductor Physics</u>
John Wiley and Sons, Inc.
New York, New York

VI SAMPLE DATA

SECTION A

<u>Experiment A-1. Measuring Light With Your Eye</u>

Comparing Illuminations:

		Ratio Of Intensities
Distance from 40-W bulb:	*84.0 cm*	
Distance from candle:	*16.0 cm*	$(\frac{84.0}{16.0})^2 = 27.6$

<u>Experiment A-3. Measuring Light With A Photovoltaic</u>

Comparing Sources Directly:

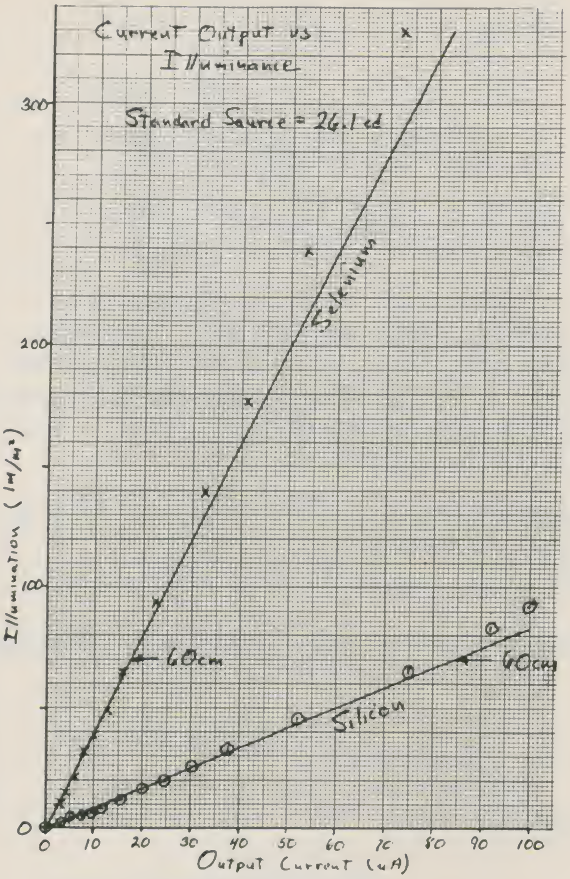
	Selenium	Silicon	Ratio Of Meter Readings: Selenium	Ratio Of Meter Readings: Silicon
Meter reading, 40-W bulb:	*100 μA*	*100 μA*		
Meter reading, candle:	*4 μA*	*11 μA*	*25*	*9.1*

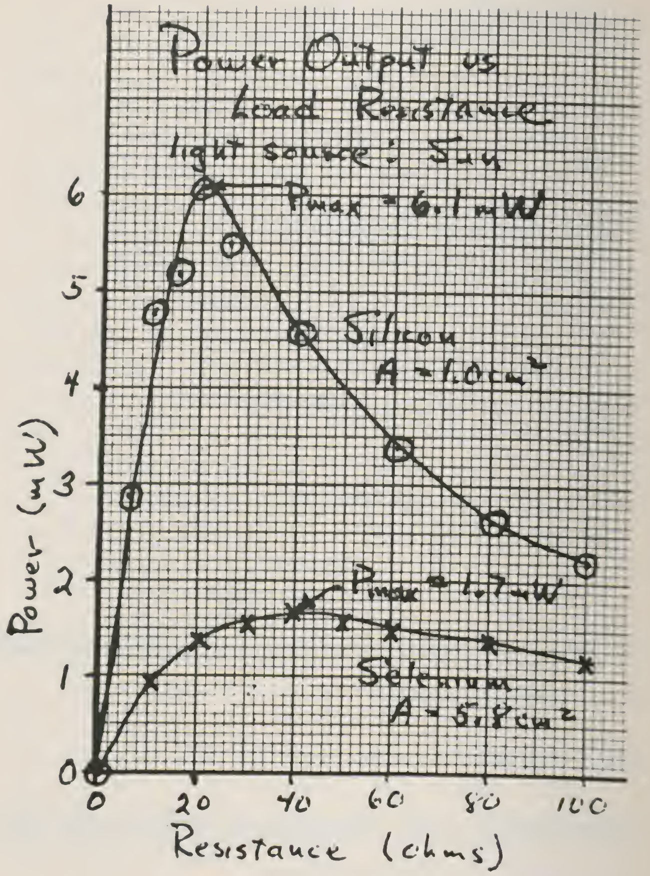
Comparing Illuminations:

			Ratio Of Intensities	
Distance from 40-W bulb:	*26.7 cm*	*83.8 cm*		
Distance from candle:	*5.1 cm*	*25.4 cm*	$(\frac{26.7}{5.1})^2 = 27.4$	$(\frac{83.8}{25.4})^2 = 10.8$

Actual Rated Output:

		Ratio Of Intensities
40-W bulb:	*26.1 cd*	
Candle:	*1.0 cd*	*26.1*





Sensitivity

Silicon: $\underline{S} = \dfrac{100\ \mu A}{83\ \text{lux}}$

$= 1.20\ \dfrac{\mu A}{\text{lux}}$

$\dfrac{1}{\underline{S}} = .83\ \dfrac{\text{lux}}{\mu A}$

Selenium: $\underline{S} = \dfrac{80\ \mu A}{319\ \text{lux}}$

$= .25\ \dfrac{\mu A}{\text{lux}}$

$\dfrac{1}{\underline{S}} = 4.0\ \dfrac{\text{lux}}{\mu A}$

Sensitivity can be increased by adding a current amplifier.

Power Per Unit Area

Silicon: $\underline{P}_{max} = \dfrac{6.1 \times 10^{-3}\ W}{1.0 \times 10^{-4}\ m^2}$

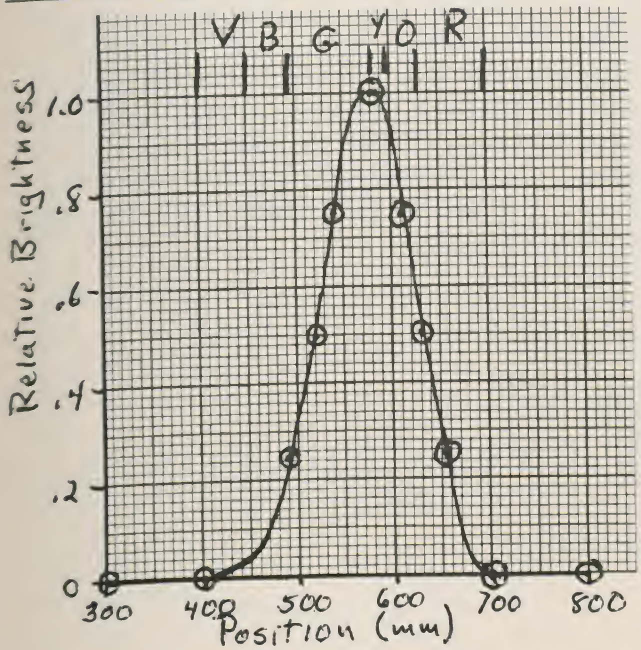
$= 61\ \dfrac{W}{m^2}$

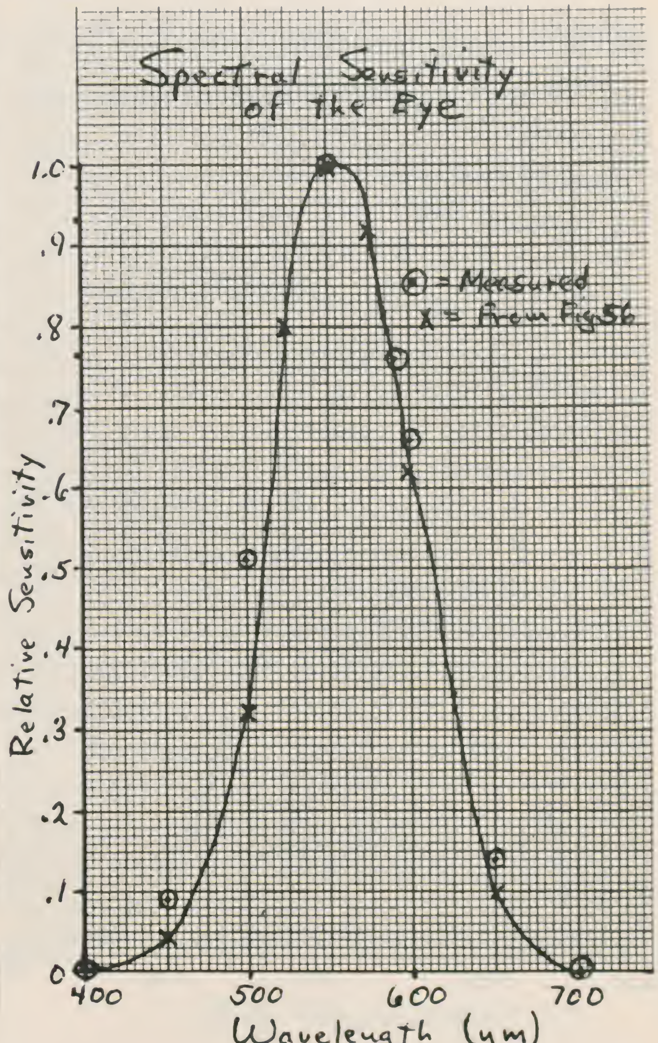
Selenium: $\underline{P}_{max} = \dfrac{1.7 \times 10^{-3}\ W}{5.8 \times 10^{-4}\ m^2}$

$= 2.9\ \dfrac{W}{m^2}$

SECTION B

Experiment B-1. Spectral Sensitivity Of The Eye

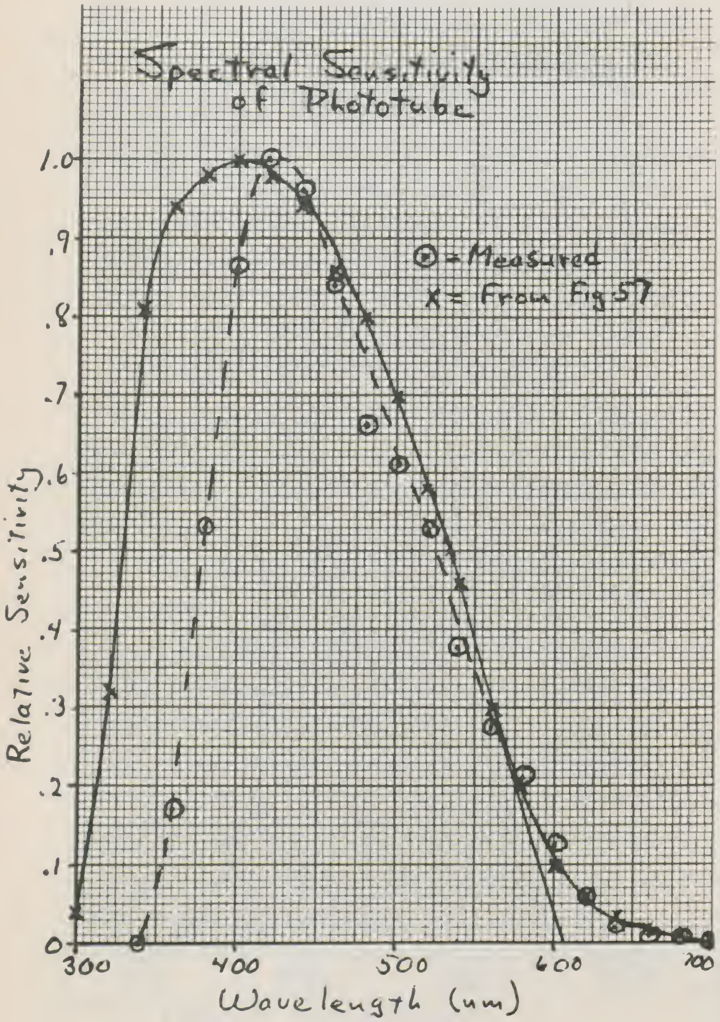




From Graph Above

λ (nm)	Relative Brightness $\underline{O}$	Relative Sensitivity $\underline{S}=\underline{O}/\underline{E}$	$\underline{S}$ (normalized)
400	0	0	0
450	.03	.25	.09
500	.30	1.4	.51
550	.90	2.6	1.0
580	1.0	2.0	.76
600	.94	1.7	.66
650	.28	.38	.14
700	0	0	0

Experiment B-3. Spectral Sensitivity Of A Phototube



The data opposite agree well with the published data for the type 929 phototube for wavelengths greater than about 420 nm. The sharp cutoff at shorter wavelengths is due to the absorbance of the glass in the lenses of the projectors used as a light source. Flint glass, of which most lenses are made, has a sharp absorption edge at about 380 nm in agreement with the data shown opposite.

$$\lambda_c = 610 \text{ nm}$$

$$\phi = \frac{hc}{\lambda_c}$$

$$= \frac{6.6 \times 10^{-34} \text{ Js} \times 3 \times 10^{8} \text{ m/s}}{610 \times 10^{-9} \text{ m}}$$

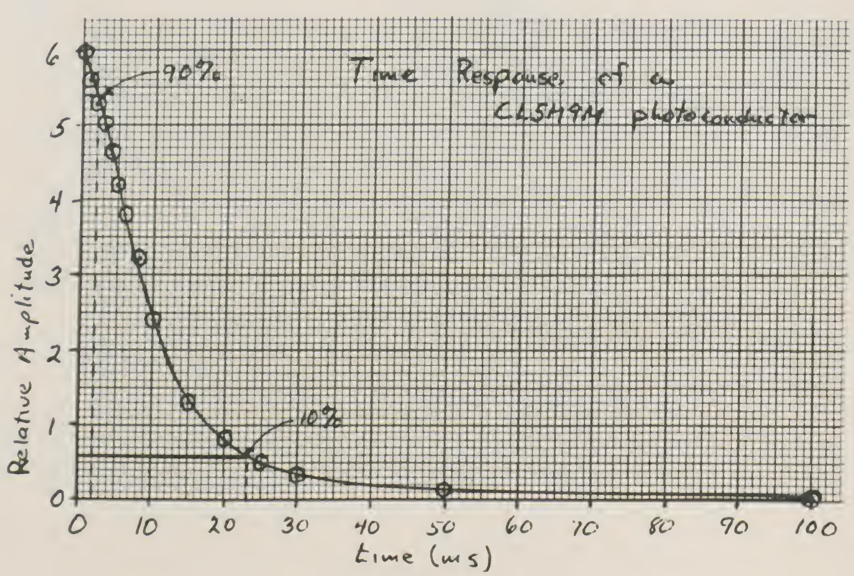
$$\phi = 3.2 \times 10^{-9} \text{ J} \times \frac{1 \text{ eV}}{1.6 \times 10^{-19} \text{ J}}$$

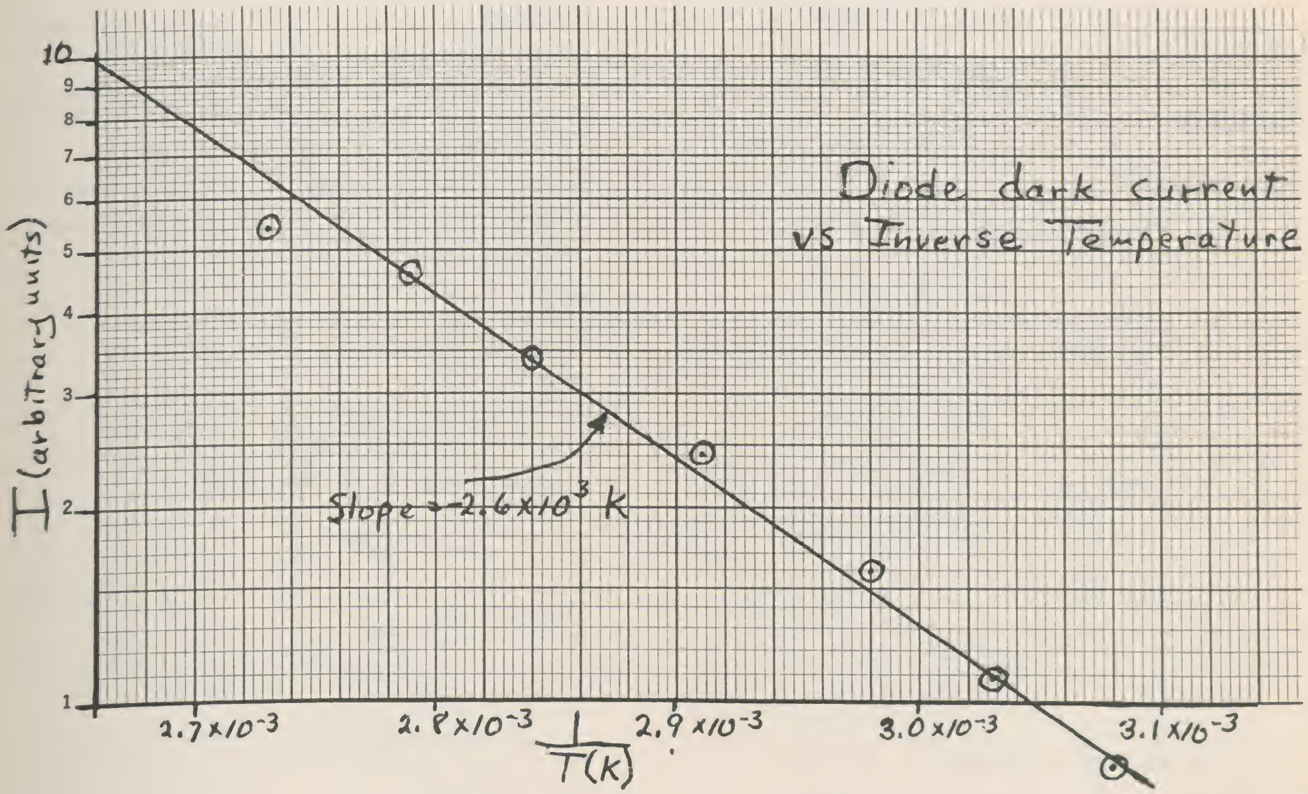
$$= 2 \text{ eV}$$

SECTION C

Experiment C-1. Measuring Response Time Of A Photoconductor

Rise Time = .6 μs
Decay Time = 21 ms





Estimating The Energy Gap

Spectral Cutoff Method:

$\lambda_c \approx 1100$ nm

$$f_c = \frac{c}{\lambda_c}$$

$$= \frac{3 \times 10^8 \text{ m/s}}{1.1 \times 10^{-6} \text{ m}}$$

$$= 2.7 \times 10^{14} \text{ Hz}$$

$$E_g = hf_c$$

$$= 6.6 \times 10^{-34} \frac{\text{J}}{\text{Hz}} \times 2.7 \times 10^{14} \text{ Hz}$$

$$= 1.8 \times 10^{-19} \text{ J} \times \frac{1 \text{ eV}}{1.6 \times 10^{-19} \text{ J}}$$

$$= 1.1 \text{ eV}$$

Thermal Drift Method:

$$\text{Slope} = \frac{\Delta \log I}{\Delta\left(\frac{1}{T(K)}\right)}$$

$$= \frac{1}{(2.66-3.05) \times 10^{-3} \ (K^{-1})}$$

$$= -2.6 \times 10^3 K$$

$$E_g = -\frac{2k}{.434} \times \text{Slope}$$

$$= + \frac{2 \times 1.38 \times 10^{-23} \text{J/K}}{.434} 2.6 \times 10^3 \text{ K}$$

$$= 1.66 \times 10^{-19} \text{J} \times \frac{1 \text{ eV}}{1.6 \times 10^{-19} \text{ J}}$$

$$= 1.04 \text{ eV}$$

The value of E_g for S_i at room temperature is 1.12 eV. The values determined by the two methods above and opposite agree well with this.

VII SOLUTIONS TO QUESTIONS AND PROBLEMS

SECTION A

Problems

1. $I = LR^2$

$= 100 \frac{lm}{m^2} (10\ m)^2$

$= 10^4\ lm$

2. $L = \frac{I}{R^2}$

$= \frac{1000\ cd}{(2\ m)^2}$

$= 250 \frac{lm}{m^2}$

$F = LA$

$= 250 \frac{lm}{m^2} (.01\ m)^2$

$= .025\ lm$

3. $R^2 = \frac{I}{L}$

$= \frac{64\ cd}{4\ lux}$

$= 16\ m^2$

$R = 4\ m$

4. The fluorescent tube is not a good approximation to a point source at one meter so that the Inverse Square Radiation Law does not apply.

SECTION B

Questions

1. Neither, but it has both wave- and particle-like properties.
2. Wave: reflection, refraction, interference and diffraction.

   Particle: interacts locally with an electron, giving it all its energy.
3. The same way as the phototube, i.e., measure its current output as a function of wavelength from a source with a broad spectral distribution, being sure to correct for the spectral distribution of the source.

Problems

1. a) $f = \frac{c}{\lambda}$

$= \frac{3 \times 10^8\ m/s}{500 \times 10^{-9}\ m}$

$= 6 \times 10^{14}\ Hz$

b) $E = hf$

$= 6.6 \times 10^{-34}\ Js \times 6 \times 10^{14}\ s^{-1}$

$= 4 \times 10^{-19}\ J$

2. a) $\lambda = \frac{c}{f}$

$= \frac{3 \times 10^8\ m/s}{10^8\ s^{-1}}$

$= 3\ m$

b) $E = hf$

$= 6.6 \times 10^{-34}\ Js \times 10^8\ s^{-1}$

$= 6.6 \times 10^{-26}\ J$

3. $f = \frac{E}{h}$

$= \frac{4 \times 10^{-19}\ J}{6.6 \times 10^{-34}\ Js}$

$= 6 \times 10^{14}\ Hz$

$\lambda = \frac{c}{f}$

$= \frac{3 \times 10^8}{6 \times 10^{14}}$

$= 500$ nm (yellow)

SECTION C

Questions

1. The fast rise time is due to the fact that the first photons striking the semiconductor immediately activate conducting electron-hole pairs. The slow decay is due to the time it takes for the conduction electrons to find a hole to recombine with.
2. See page 60.
3. Zero, since there are no conduction electrons.

   Yes, it is still light sensitive.

Problems

1. $\log \underline{i}_1 = \underline{C} - .43 \dfrac{\underline{Eg}}{2\underline{k}\underline{T}_1}$

$$\log \underline{i}_2 = \underline{C} - .43 \frac{\underline{Eg}}{2\underline{k}\underline{T}_2}$$

$$\log \underline{i}_1 - \log \underline{i}_2 = -.43 \frac{\underline{Eg}}{2\underline{k}} \left(\frac{1}{\underline{T}_1} - \frac{1}{\underline{T}_2}\right)$$

$$\underline{Eg} = + \frac{\underline{k}}{.22} \log \left(\frac{\underline{i}_2}{\underline{i}_1}\right) \frac{1}{\left(\frac{1}{\underline{T}_1} - \frac{1}{\underline{T}_2}\right)}$$

$$= \frac{1.38 \times 10^{-23}\ \text{J/K}}{.22} \times \log 2 \times \frac{1}{\left(\frac{1}{300\text{K}} - \frac{1}{350\text{K}}\right)}$$

$$= .41 \times 10^{-19}\ \text{J}$$

2. $\underline{f}_{\underline{c}} = \dfrac{\underline{Eg}}{\underline{h}}$

$$= \frac{.41 \times 10^{-19}\ \text{J}}{6.6 \times 10^{-34}\ \text{Js}}$$

$$\underline{f}_{\underline{c}} = 6.2 \times 10^{13}\ \text{Hz}$$

3. $\underline{f}_{\underline{c}} = \dfrac{\underline{c}}{\lambda_{\underline{c}}}$

$$= \frac{3 \times 10^{8}\ \text{m/s}}{750 \times 10^{-9}\ \text{m}}$$

$$= 4 \times 10^{14}\ \text{Hz}$$

$$\underline{Eq} = \underline{hf}_{\underline{c}}$$

$$= 6.6 \times 10^{-34}\ \text{Js} \times 4 \times 10^{14}\ \text{s}^{-1}$$

$$= 2.6 \times 10^{-19}\ \text{J}$$

4. $\underline{f} = \dfrac{\underline{c}}{\lambda}$

$$= \frac{3 \times 10^{8}\ \text{m/s}}{10^{-6}\ \text{m}}$$

$$= 3 \times 10^{14}\ \text{Hz}$$

$$\underline{E} = \underline{hf}$$

$$= 6.6 \times 10^{-34}\ \text{Js} \times 3 \times 10^{14}\ \text{s}^{-1}$$

$$= 2 \times 10^{-19}\ \text{J} \times \frac{1\ \text{eV}}{1.6 \times 10^{-19}\ \text{J}}$$

$$\underline{E} = 1.25\ \text{eV}$$

VIII POST-TESTS

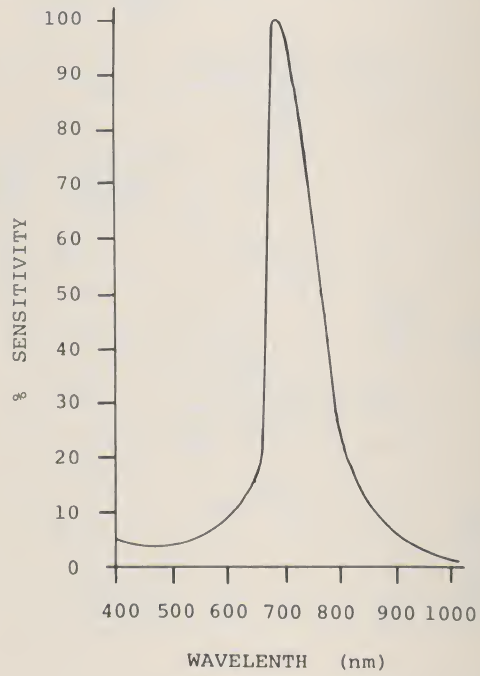
Test I

1. List five properties of photodetectors and briefly explain each.
2. At approximately what distance in outer space can the earth be considered a point source of reflected sun light?
3. A 1000-W photoflood light is listed as producing an illuminance of 5000 lux at 3 m. What is its intensity from that direction?
4. Why is silicon used instead of selenium for making solar cells?
5. Sketch a graph of the spectral sensitivity of the human eye. Label the horizontal axis in proper units of wavelength and accurately locate the ends and peak of the spectral curve.

6. Suppose you disperse sunlight into its component colors with a diffraction grating and then measure the output of a photovoltaic cell for each of the colors. Give an expression for the relative spectral sensitivity of the photovoltaic for each color and explain each term in it.
7. Of the following light phenomena, which are best explained by the wave picture and which by the particle picture of light?
   a) reflection
   b) photoelectric effect
   c) diffraction
   d) interference
   e) photo-activation
   f) refraction
8. The long-wavelength cutoff of a given phototube is 750 nm. What is the work function energy of the photocathode material?
9. Describe using energy level diagrams the difference between a conductor, an insulator and a semiconductor.
10. Does the resistance of a photoconductor increase or decrease with illumination? Why?
11. If the leakage current of a diode increases by a factor of 10 from 50°C to 100°C, what is the energy gap in the diode material?

Test II

1. List five properties of photodetectors and briefly explain each.
2. State and give an expression for the Inverse Square Radiation Law as it applies to light. Under what conduction can it be used for a given light source?
3. Describe a way to measure the relative intensities of two similar light sources using an uncalibrated light meter.
4. Why is selenium more often used than silicon for photographic light meter applications?
5. Sketch the visible part of the electromagnetic spectrum. Label the wavelength in proper units and show the approximate range of each spectral color. Also label the regions adjacent to the visible.
6. Suppose you use a photodetector with a certain spectral sensitivity S to measure the output of a light source whose spectral distribution is D. Give an expression for the expected relative output O of the detector at each wavelength.
7. List three wave-like and two particle-like characteristics of light.
8. A certain photocathode material has a work function of 2.65×10^{-19} J. What long-wavelength cutoff will it give?
9. Describe using energy level diagrams the difference between a conductor, an insulator and a semiconductor.
10. Does the dark current of a diode increase or decrease with temperature? Why?
11. What is the energy gap (in eV) of the material in a photoconductor whose spectral sensitivity is shown in the figure?



Solutions To Post-Tests

Test I

1. See pages 7 and 8.
2. The earth's diameter is approximately 8000 mi. Therefore at 10 x 8000 mi = 80,000 mi the earth acts like a point source.

3. $\underline{I} = \underline{LR}^2$

   $= 5000 \text{ lux} \times (3 \text{ m})^2$

   $= 45{,}000 \text{ candela}$

4. Because it produces about 20 times as much electrical power for a given solar illumination.
5. See Figure 56.

6. $\underline{S} = \frac{\underline{O}}{\underline{D}}$

   where:

   $\underline{S}$ = relative spectral sensitivity of the photovoltaic cell for each color

   $\underline{O}$ = relative output of the photovoltaic cell for each color

   $\underline{D}$ = relative spectral distribution of the sun for each color

7. a) wave
   b) particle
   c) wave
   d) wave
   e) particle
   f) wave

8. $\underline{f}_{\underline{c}} = \frac{\underline{c}}{\lambda_{\underline{c}}}$

   $= \frac{3 \times 10^8 \text{ m/s}}{750 \times 10^{-9} \text{ m}}$

   $= 4 \times 10^{14} \text{ Hz}$

   $\phi = \underline{hf}_{\underline{c}}$

   $= 6.62 \times 10^{-34} \text{ Js} \times 4 \times 10^{14} \text{s}^{-1}$

   $\phi = 2.6 \times 10^{-19} \text{ J}$

9. See page 61.
10. Decreases. An increase in illumination produces more photo-activated electrons which will conduct current. An increase in conductivity is equivalent to a decrease in resistance.

11. $\underline{Eq} = -\frac{2k}{.434} \frac{\Delta \log \underline{I}}{\Delta (\frac{1}{\underline{T}})}$

    $= 1.51 \times 10^{-19} \text{ J} \times \frac{1 \text{ eV}}{1.6 \times 10^{-19} \text{ J}}$

    $= .95 \text{ eV}$

Test II

1. See pages 7 and 8.
2. The Inverse Square Law of Radiation describes the decrease in energy with distance from a point source radiator. For light, this means the decrease in illumination, $\underline{L}$, from a source of intensity $\underline{I}$ at a distance $\underline{R}$:

   $$\underline{L} = \frac{\underline{I}}{\underline{R}^2}$$

   This can be used with sufficient accuracy at distances greater than 10 times the largest source dimension.
3. Measure the distance from each source at which the light meter gives equal readings, making sure that both distances are at least 10 times the largest source dimension. The ratio of the intensities can then be calculated from:

   $$\frac{\underline{I}_1}{\underline{I}_2} = \frac{\underline{R}_1^{\,2}}{\underline{R}_2^{\,2}}$$

4. Because its spectral sensitivity is more nearly matched to that of the human eye.
5. See Figure 52.
6. $\underline{O} = \underline{SD}$.

7. Wave: reflection, refraction, interference and diffraction

   Particle: photoelectric effect, photo-activation in semiconductors

8. $$f_c = \frac{\phi}{h}$$

$$= \frac{2.65 \times 10^{-19}\ J}{6.62 \times 10^{-34}\ Js}$$

$$= 4 \times 10^{14}\ Hz$$

$$\lambda_c = \frac{c}{f_c}$$

$$= \frac{3 \times 10^{8}\ m/s}{4 \times 10^{14} s^{-1}}$$

$$= 750\ nm$$

9. See page 61.
10. Increases. As the temperature increases, there are more thermally activated electrons to conduct current.

11. $$\lambda_c = 830\ nm$$

$$f_c = \frac{c}{\lambda_c}$$

$$= \frac{3 \times 10^{8}\ m/s}{.83 \times 10^{-6}\ m}$$

$$= 3.6 \times 10^{14}\ Hz$$

$$Eg = hf_c$$

$$= 6.62 \times 10^{-34}\ Js \times 3.6 \times 10^{14} s^{-1} \times \frac{1\ eV}{1.6 \times 10^{-19} J}$$

$$= 1.5\ eV$$

IX LIST OF APPARATUS

SECTION A

Room that can be darkened
Standard candle
Standard 40-watt bulb
Variac, or equivalent, to set proper ac voltage for standard bulb
Meter stick
Black cloth or other light-absorbing material
Silicon photovoltaic cell: $A \geq 1cm^2$
Selenium photovoltaic cell: $A \geq 5cm^2$
Ammeter: 0-100μA, input resistance $\leq 1000\Omega$
Box, or some other housing, for the photovoltaic cells. It should be light tight, blackened on the inside, and have a hole in it slightly larger than the photovoltaic cell. The photocell should be mounted several centimeters behind the hole so that the light shines directly on it. There should also be a means for making electrical connections to the photocells from outside the box.
OPTIONAL: Voltmeter: 0-.5 volt full scale or less, input impedance greater than 5kΩ. Resistance box: (or selection of resistors) from 10Ω to 1000Ω.

SECTION B

High-intensity, focused light source (e.g., a slide projector)
Diffraction grating (transmission or reflection) of relatively good quality and about 15,000 lines/in.
Meter stick and ring stand with clamps
Slit (about 1-mm gap): Can be made from two razor blades and an old slide
Phototube: RCA #929 vacuum type
Ammeter: 0-100μA full scale
Horseshoe magnet: gap $\geq$ 1-1/8 in.
Battery (0-6V) and clip leads
Amplifier with variable zero and gain controls, gain 0-100
Voltmeter: 0-2V full scale
OPTIONAL: Variable Resistor: 0-10kΩ

SECTION C

Photoconductor: Clairex Type CL5M9M
Stroboscope
Oscilloscope

Battery (2): 6V or 9V
Resistors: 500Ω and 1000Ω
Clip leads
Diode: Silicon
Amplifier with variable zero
and gain control, gain 0-2000
Voltmeter: 0-2V
Variable temperature water bath: 0-100°C
Thermometer: 0-100°C
Thin-walled plastic bag
Variable Resistor: 0-1MΩ
Silicon Controlled Rectifier (SCR):
e.g., GE type C106
6-Volt buzzer or relay
Capacitor (100μF) for use with buzzer
Switch

INSTRUCTOR'S MANUAL FOR THE PILE DRIVER

I INTRODUCTION

The Pile Driver module covers the physics concepts, definitions, and principles of the mechanics of linear motion. The module emphasizes the following: definitions of speed, acceleration, mass, force, work, energy, and momentum. Also emphasized are the concepts of weight and acceleration due to gravity. The principles covered include: Newton's Laws of Motion, conservation of energy, and momentum.

II SPECIAL PREREQUISITES

There are no special prerequisites for this module except that for the Physics of Technology series as a whole. A recent course in high school algebra is sufficient as a math prerequisite for this module. A course in college algebra is more than sufficient.

III TABLE OF CONTENTS OF THE MODULE

Summary
Worksheets

IV GOALS

1. Know the "set" of a pile, with a given pile driver, changes with the pile's penetration into uniform ground.
2. Know the general effects of hammer weight and free-fall distance on the set of a pile.
3. Understand in a general way how the speed of a freely falling object changes with time.
4. Understand qualitatively how the speed of free fall is related to weight and air resistance.
5. Know the definitions of average speed, instantaneous speed, and acceleration for straight-line motion.
6. Know the relation between distance traveled, initial speed, acceleration, and time for a constant-acceleration straight-line motion.
7. Know the direct relation between final speed, acceleration, and distance traveled for a straight-line constant acceleration where the initial speed is zero.
8. Be able to work free-fall problems on the earth's surface.
9. Understand the definition and concept of mass.
10. Know the definitions of force and weight.
11. Know the mathematical definitions of work, kinetic energy, and gravitational potential energy.
12. Understand the principle of conservation of energy.
13. Be able to apply the principle of conservation of momentum.

V. DISCUSSION OF ACTIVITIES

a. Laboratory Activities

Experiment A-1. Driving a Pile with a Falling Weight

The purpose of this experiment is to determine some of the factors affecting the driving of a pile into uniform material. The pile driver may be constructed simply by attaching a screw eyelet in a convenient place in the ceiling of the lab and using a heavy (1 to 2 kg) cylindrical metal object with an eyelet attached to the top. An iron cylinder 2 inches in diameter and 6 inches long does nicely. 7- or 8-inch spikes from the hardware store work well for the piles, and a scrap piece of soft wood 4 x 4 such as pine or redwood works well for a uniform material. (Watch for knots in the wood.)

The apparatus needed for one set-up of Experiment A-1 is as follows:

Item	Quantities
Pile	2 or 3
4 x 4 scrap of wood	2 or 3
Hammer	1
Meter stick	1

Experiment B-1. Motion of a Freely Falling Body

The purpose of this experiment is to determine the motion of an object as it falls without restraint. The "Behr" free-fall apparatus works very nicely. Other methods work equally well.

The apparatus needed for one set-up of Experiment B-1 is as follows:

Item	Quantities
Free-Fall Apparatus	1
Meter stick	1

Experiment C-1. Energy Transfer in Pile Driving

The purpose of this experiment is to demonstrate that there is an energy "loss" between the potential energy of the hammer and the work done on moving the pile into the wood. The added pile weight can be constructed by drilling an appropriate hole in the same kind of cylinder used for the hammer.

The apparatus needed for one set-up of Experiment C-1 is as follows:

Item	Quantities
Pile	1
4 x 4 scrap	2 or 3
Hammer	1
Weight (attached to the nail)	1
Meter stick	1

b. Other Activities

The Pile Driver module has been designed for use in an introductory physics course which has two or three hours of laboratory time per week and three fifty-minute classes per week.

Physics of Technology modules can be used most effectively if you avoid lectures entirely. Class time can be most interesting and helpful to students if you will spend that time doing demonstrations, discussing the laboratory work, and asking students about questions and problems in the module. A list of resource material is included below.

c. Resource Material

A. 16-mm Sound Films

"Energy and Work"; Modern Learning Aids, N.Y., N.Y.

B. 8-mm Film Loops

1. "Pile Driver", Thornton Assoc.
2. "Method of Measuring Energy", National Film Board of Canada, Montreal, Canada
3. "Free Fall", Nat. Film Brd.
4. "Falling Bodies", International Communication Films, Santa Ana, Calif.
5. "Potential Energy", Bailen Film Assoc., Los Angeles, Calif.
6. "Work", B.F.A.

C. Transparencies

1. Definition of Work, No. 6830, Frey Scientific Co.
2. Graph of Uniform Velocity, No. 6817, Frey
3. Graph of Variable Velocity, No. 6818, Frey
4. Potential Energy, No. M-6755, Frey

VI SAMPLE DATA

Experiment A-1

1. m_1 = 47.0 g, m_2 = 47.2 g, m_3 = 46.6 g
   M_S = 1.30 kg, M_L = 2.69 kg
2. L_1 = 15.3 cm
3. D = 12.7 cm

4-10.

Table 1
Small Weight at Height of 200 cm

D (cm)	s (cm)	P (cm)
12.7	-	2.6
12.0	0.7	3.3
11.5	0.5	3.8
11.0	0.5	4.3
10.6	0.4	4.7
10.2	0.4	5.1
9.8	0.4	5.5
9.4	0.4	5.9
9.1	0.3	6.2
8.7	0.4	6.6
8.5	0.2	6.8
8.1	0.4	7.2
7.8	0.3	7.5
7.5	0.3	7.8

11. L_2 = 15.20 cm

12.

Table 2
Small Weight at Height of 100 cm

D (cm)	s (cm)	P (cm)
12.7	-	2.5
12.3	0.4	2.9
12.0	0.3	3.2
11.9	0.1	3.3
11.6	0.3	3.6
11.3	0.3	3.9
11.2	0.1	4.0

Table 2 (cont.)

D (cm)	s (cm)	P (cm)
11.0	0.2	4.2
10.8	0.2	4.4
10.6	0.2	4.6
10.4	0.2	4.8
10.2	0.2	5.0
10.1	0.1	5.1
9.8	0.3	5.4
9.6	0.2	5.6
9.4	0.2	5.8
9.2	0.2	6.0
9.1	0.1	6.1
9.0	0.1	6.2
8.9	0.1	6.3
8.8	0.0	6.3
8.7	0.2	6.5

13. L_3 = 18.2 cm

Table 3
Large Weight at Height of 100 cm

D (cm)	s (cm)	P (cm)
15.7	-	2.5
14.8	0.9	3.4
14.0	0.8	4.2
13.5	0.5	4.7
13.0	0.5	5.2
12.6	0.4	5.6
12.2	0.4	6.0
11.9	0.3	6.3
11.5	0.4	6.7
11.2	0.3	7.0
10.8	0.4	7.4
10.5	0.3	7.7
10.2	0.3	8.0

15. The mass of the hammer, the height of fall, and the penetration.
16. The set decreases.
17. As the height increases, the set increases.
18. As the mass increases, the set increases.

Experiment B-1

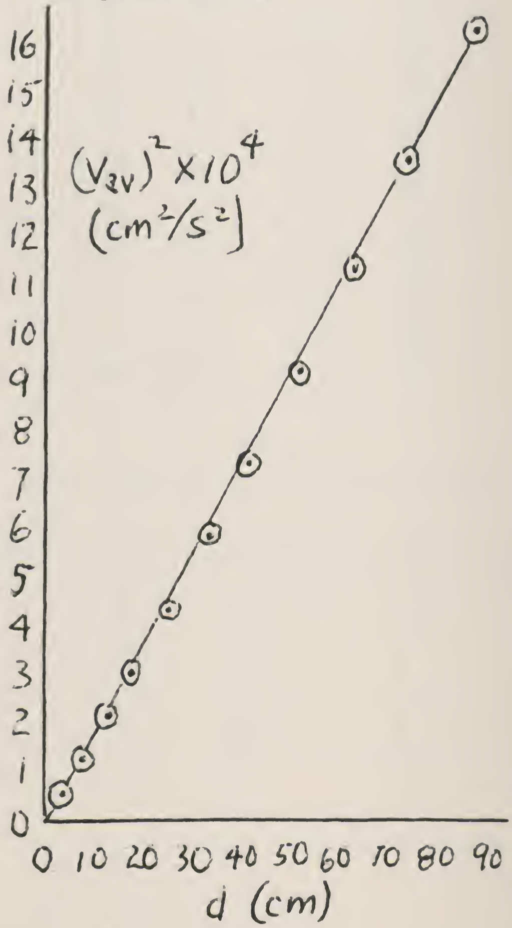
1. Yes
2. Increase

3-6.

Table 4.

Time $t = 0$	Distance Between Marks (Δd)	Total Distance Fallen (d)	Average Speed ($v_{av} = \Delta d/\Delta t$)	Average Acceleration ($a_{av} = \Delta v_{av}/\Delta t$)
t_1	2.5 cm	4.3 cm	75 cm/s	
t_2	3.6	7.9	108	990 cm/s^2
t_3	4.8	12.6	144	1080
t_4	5.7	18.4	171	810
t_5	6.9	25.2	207	1080
t_6	8.0	33.3	240	990
t_7	9.0	42.3	270	900
t_8	10.1	52.4	303	990
t_9	11.2	63.5	336	990
t_{10}	12.3	75.7	369	990

8. Average of Accelerations 981 cm/s^2. 11. See graph below.
10. No.



12. Yes.
13. 1800.
14. cm/s^2.
15. A little less than 1/2.

Experiment C-1

1. $\underline{m}$ = 47 grams
   $\underline{L}_1$ = 16 cm

2.

Drop Number	Top of Nail to Wood Distance $\underline{x}_i$	Set $\underline{S}$ $\underline{x}_i - \underline{x}_{i-1}$	Penetration $\underline{P}$ $\underline{L}_1 - \underline{D} - \underline{x}_i$
0	$\underline{x}_0$ = 11.9 cm	-	4.1 cm
1	$\underline{x}_1$ = 11.7 cm	0.2 cm	4.3 cm
2	$\underline{x}_2$ = 11.4 cm	0.3 cm	4.6 cm
3	$\underline{x}_3$ = 11.2 cm	0.2 cm	4.8 cm
4	$\underline{x}_4$ = 11.0 cm	0.2 cm	5.0 cm
5	$\underline{x}_5$ = 10.8 cm	0.2 cm	5.2 cm
6	$\underline{x}_6$ = 10.6 cm	0.2 cm	5.4 cm
7	$\underline{x}_7$ = 10.4 cm	0.2 cm	5.6 cm
8	$\underline{x}_8$ = 10.2 cm	0.2 cm	5.8 cm

Mass of Hammer $\underline{m}_H$ = 1.296 kg

3. $\underline{f}_o$ is large compared to $\underline{cP}$.
4. $\underline{m_H gh}$ = 12.7 J.
5. $\underline{F}_{av}$ = $\underline{mHgh}/\underline{S}$ = 12.7 J/2 x 10^{-3}m
   = 6400 N.

6. $\underline{h}$ = 100 cm
   $\underline{m}$ = 1.290 Kg
   $\underline{L}_1$ = 16 cm

Drop Number	Top of Nail to Wood Distance $\underline{x}_i$	Set $\underline{S}$ $\underline{x}_i - \underline{x}_{i-1}$	Penetration $\underline{P}$ $\underline{L}_1 - \underline{D} - \underline{x}_i$
0	$\underline{x}_o$ = 13.0 cm	-	3.0 cm
1	$\underline{x}_1$ = 12.9 cm	0.1 cm	3.1 cm
2	$\underline{x}_2$ = 12.7 cm	0.2 cm	3.3 cm
3	$\underline{x}_3$ = 12.6 cm	0.1 cm	3.4 cm
4	$\underline{x}_4$ = 12.5 cm	0.1 cm	3.5 cm
5	$\underline{x}_5$ = 12.4 cm	0.1 cm	3.6 cm
6	$\underline{x}_6$ = 12.2 cm	0.2 cm	3.8 cm
7	$\underline{x}_7$ = 12.1 cm	0.1 cm	3.9 cm
8	$\underline{x}_8$ = 12.0 cm	0.1 cm	4.0 cm

Mass of Hammer $\underline{m}_H$ = 1.296 kg

$\underline{m_H gh}$ = 12.7 J

$$\underline{F}_{av} = \frac{\underline{mHgh}}{\underline{S}} = \frac{12.7 \text{ J}}{1.2 \times 10^{-3} \text{ m}} = 10{,}000 \text{ N.}$$

7. I did not get the same $\underline{F}_{av}$ so equation (26) must be invalid.

Experiment C-2

1. About 1.
2. Yes. Yes.
3. Increase.
4. Friction.
5. Smaller meter reading change.

VII SOLUTIONS TO PROBLEMS

The problems and questions are an important part of the module. Questions should be discussed in class, so far as possible. Many of the problems should be discussed in class, but if answers are provided, many students will work the problems outside of class and check their own work. The problem answers below are provided so that you can copy them and distribute them to students, if you wish.

1. 3.33 m/s.
2. 5000 s = 83.3 min = 1.4 hr.
3. 2.5 m/s^2.
4. 66.6 m/s^2.
5. 5 s.
6. -2.9 m/s.
7. -39.6 m/s.
8. 6.6 s, 13.2 s.
9. -
10. 215 m.
11. 1.2 m.
12. 0.32 s.
13. 22.2 m/s^2.
14. 2.2 m/s, 3.1 m/s, 490 m, No.
15. 2.5 kg.
16. 1.6×10^{-21} m/s^2.
17. 5 N, -5 N.
18. 1.96 N.
19. 0.69 N.
20. 75 N.
21. 8030 N downward, 9.5 m/s^2 downward.
22. 33,333 N.
23. -
24. 11,760 J, 11,760 J, 11,760 J, 5.4 m/s.
25. 326 N.
26. 5.4×10^5 N.
27. 5.48 m/s.
28. 29400 J.
29. 686 J.

VIII POST-TESTS

Section A

1. How would you expect the set of a pile to change after it has been driven a number of times into uniform ground? Why?
2. Which of the following statements best describes the effects of hammer weight and free-fall distance on the set of a pile?
   a. The set decreases as free-fall distance increases and decreases as hammer weight increases.
   b. The set decreases as free-fall distance decreases and decreases as hammer weight increases.
   c. The set decreases as free-fall distance decreases and decreases as hammer weight decreases.
   d. The set increases as free-fall distance increases and decreases as hammer weight increases.
3. Place the following speeds of a freely falling object in the proper time order, earliest first and latest last: 200 cm/s, 15.8 cm/s, 65.5 cm/s, 12.2 cm/s, 143 cm/s.
4. A three-gram leaf, a three-gram acorn, and a five-gram bird's egg fall out of an oak tree from the same branch. In what order would you expect them to hit the ground?

Answers

1. The set will decrease because the friction increases with penetration.
2. c.
3. 12.2 cm/s, 15.8 cm/s, 65.5 cm/s, 143 cm/s, 200 cm/s.

4. First the acorn and bird egg and then the leaf.

Section B

1. An automobile changes its speed from 21 m/s to 35 m/s in 7 s. What is its acceleration during this time?
2. A modified stock car drag racer covers 500 m in 9 seconds from a standing start. What is its acceleration in m/s/s?
3. If the maximum acceleration of a bus is 1.5 m/s/s, how far does it travel in reaching a velocity of 10 m/s from a stop?
4. A Dodger baseball player pops up for the final out in the series. If the ball is in the air for 5 seconds before it is caught and the Oakland stadium roof is 80 feet above the playing field, will the ball go higher than the roof? How high does it go?

Answers
1. 2 m/s/s.
2. 12.5 m/s/s.
3. 33.3 m.
4. Yes, 100 ft.

Section C

1. Two skaters on roller skates push each other to separate. If one skater has a mass of 90 kg and while separating has an acceleration which is 2/3 that of the other skater, what is the mass of the other skater?
2. If a person has a mass of 4 slugs, what is that person's weight in pounds?
3. How much work is done by a pile driver in lifting an 8000-kg hammer a distance of 1 meter?
4. A pile driver hammer strikes the pile exerting an average downward force of 5×10^4 N. If the set of the pile was 2.5 cm, what work did the hammer do on the pile?

Answers
1. 60 kg.
2. 128 lb.
3. 78,400 J.
4. 1250 J.

IX LIST OF APPARATUS

Most of the equipment needed in this module is considered to be "normal" lab equipment, and no source is listed for such equipment.

Item	Quantity	Source
Pile	2 or 3	10- to 18-cm nail from Hardware store
4 x 4 scrap of wood	2 or 3	
Hammer	2	Iron cylinders of mass 1 to 4 kg (one must have twice the mass of the other)
Meter stick	1	
Free-fall apparatus	1	Such as Behr apparatus from Cenco
Weight to attach to the pile	1	(described in Experiment C-1)
Thermistor	1	Such as Fenwal Electronics GA51J1.
Amplifier-Power supply	1	Thornton Assoc. No. SRM-100 and APS-101

Thermal contact cement (such as Omega Eng. Inc. Thermcoat)

CONTENTS

I INTRODUCTION

The general aim of this module is to produce an awareness of the importance of temperature and heat flow in the behavior of practical devices and systems. This involves a knowledge of how to measure both temperature and thermal power under diverse conditions, as well as an understanding the basic parameters such as heat capacity and thermal resistance which are used to describe a thermal system. The distinction between steady-state and transient behavior is emphasized and explored, and the simple laws governing growth or decay in an exponential process are revealed. The various heat transfer mechanisms (conduction, convection, radiation) are examined and discussed in considerable depth.

II SPECIAL PREREQUISITES

This module requires that the student be familiar with Ohm's law and with some basic concepts relating to electricity and temperature measurement.

III TABLE OF CONTENTS OF THE MODULE

SECTION A. MEASURING ELECTRICAL POWER AND TEMPERATURE

SECTION B. HEAT TRANSFER PROCESSES

Increasing the Rate of Heat Transfer
Other Applications
Mathematical Basis of Heat Transfer (optional)
Conduction
Convection
Radiation

SECTION C. TRANSIENT THERMAL BEHAVIOR

Examples of Thermal Behavior
Examples of Thermal Transience
Describing Transient Behavior
Other Types of Transience
Transient Oscillations
Experiment C-1. Transience in a Mercury Thermometer
Experiment C-2. Transience in a Transistor
Heating Power
Transient Temperature Behavior
The Time Constant
How to Determine the Time Constant
Transient Warming
Nonexponential Transience

IV GOALS

The objectives of the Power Transistor module have been included at the beginning of the module.

V DISCUSSION OF ACTIVITIES

This module is divided into three parts.

SECTION A

This section of the module is concerned with basic concepts as well as methods for measuring temperature and heat flow. Power is defined, and the term is seen to apply not only to electrical power but also to the rate of mechanical work and heat flow. The transistor is introduced as a type of "valve" by which power can be controlled. There is little emphasis on technological applications of the power transistor. It is simply a convenient device for revealing physical principles which apply in a great number of practical situations.

The first part deals with temperature in terms of advantages and disadvantages of different types of thermometers. Properties common to all thermometers are summarized briefly, following which the use of a copper-constantan thermocouple is discussed in detail. The initial laboratory experience involves using the thermocouple to measure transistor case temperatures. This is also done with a mercury thermometer, and the student is able to compare its performance with that of the thermocouple from several standpoints. The criteria of range, sensitivity, accuracy, and response time are introduced. Following this the general characteristics of thermocouples, thermistors, and resistance thermometers are summarized.

It should be noted that any one of several thermocouple pairs can be used for this work, although the discussion, tables, etc., in the module focus on the copper-constantan pair.

In using a thermocouple, it is important to bear in mind that as a voltage source the device has a

rather high output impedance - as much as several ohms in a typical case. Thus the voltage measuring instrument used with it should have a reasonably high input impedance to avoid loading, which would result in systematic errors in the temperature values deduced from the standard tables. Voltmeters with 10mV f.s. sensitivity are availabe but may not be suitable for this reason. The module suggests using an amplifier to boost the signal and to provide some buffering between the thermocouple and the voltmeter. One could also use a true potentiometer; however the time required for balancing would rule this out for quantitative observations of thermal transients in the final section of the module.

Some additional comments and precautions pertaining to the work of the entire module are contained in the notes on pages 8 and 10 below.

See Sections B and C for additional comments and precautions.

SECTION B

Here the work focuses on steady-state behavior of the transistor, with a connection to practical problems established via the Power Temperature Derating Curve (taken from the transistor specification sheet). A general discussion of heat flow is provided, using energy conservation as the point of departure. One important feature is an elementary introduction to ideas on thermal resistance and thermal conductivity. In an optional supplement, the analysis is carried further to deal with convection and radiation. This includes a brief discussion of emissivity and the Stefan-Boltzmann law of radiation, which gives the fourth-power dependence of radiated power on the absolute temperature.

While the experiments center around the power transistor, other devices such as a power resistor or even a soldering iron might also serve for studying heat flow. Certainly the particular transistor type used is not important, so long as the maximum dissipation is at least 100 watts or so.

For the transistor circuitry, a pre-wired board can be provided, as an aid to students with little or no wiring experience. The students may in addition have some difficulty identifying emitter, base, and collector leads on the transistor. Connecting wires with plugs should perhaps be soldered to each lead and clearly labelled. If pre-wired boards are not used, the instructor may wish to check the potentiometer wireing to be sure that clockwise rotation increases the collector current. Full counterclockwise rotation should cut off the current entirely.

<u>NOTE</u>: The metal case of the transistor is electrically connected to the collector lead. Thus some caution should be exercised when handling the completed circuit, especially if higher power supply voltages are used.

The transistor can become very hot when operating. The case temperature may on occasion approach 200°C, so one should be wary about touching it. With the fan on, the temperature should be much lower, even when the power is large. However, if the fan is accidentally removed, the transistor can burn out very quickly. Thus the derating curve should be kept handy during the experiments, and it should be consulted frequently. It is a good idea to plot the derating curve first on a separate sheet of graph paper. Then each experimental point can be added to the graph as it is taken.

For Experiment B-3, it is necessary to hold down a thermocouple junction on the heat sink, making good thermal contact. An extra threaded hole in the sink with matching screw may be convenient for that purpose. When tightening down a screw to hold the junction, care should be taken to avoid damage.

To promote thermal contact between transistor and heat sink, commercial thermal joint compound is helpful.

SECTION C

The main concern here is with the transient warming or cooling of a transistor caused by switching the power on or off. The temperature is observed and plotted versus time. The resulting exponential curve is discussed qualitatively, and then a quantitative treatment in terms of energy conservation is given. The concept of heat capacity is introduced. Together with the concept of thermal resistance (introduced in Section B), this leads to an understanding of the time constant for growth or decay of thermal transients. Methods are given for either calculating or estimating the time constant under various conditions. Finally, there is some discussion of ways to characterize the duration of non-exponential transients.

The experiments begin with some preliminary work using mercury thermometers. For data taking during these transients, the students should not worry too much about having their results be exceedingly accurate. As the module suggests, one or two quick practice runs before serious data taking begins may greatly clarify what is to be done, and especially how quickly it must be done.

The most satisfactory procedure for transient measurements is to decide beforehand on a single, reasonable time interval for separating the points. For instance, the module specifies that temperature readings can be made every three seconds when looking at transients in the mercury thermometer. Then, if it later turns out that a higher density of points is desired, this first set of readings can be simply interleaved with a second set from another run.

The experimental work with the transistor (Experiment C-2) while fairly straightforward, requires efficient procedure in order to be

completed in the time available. If necessary, different pairs of students can collaborate, with each pair concentrating on a particular aspect of the assignment during the lab period, and with a sharing of data at the end. Thus one pair of students might focus on the growth of thermal transients, while another focused on the decay. Or, the division of labor might have both pairs of students observing growth and decay of thermal transients, but at different power levels.

In instructor may wish to demonstrate, or to have students undertake as an extra credit project, the continuous recording of thermal transients using a strip-chart recorder. In this scheme, the thermocouple output is connected to the recorder input.

This directly provides a graph of voltage versus time on the chart. The time scale is determined by the chart speed. It should be emphasized that the thermocouple voltage is *not* exactly linear with the junction temperature (although nearly so). Thus, the recorder trace obtained in this way is not quite expoential, and some additional data processing may be required based on the thermocouple table.

VI SAMPLE DATA

SECTION A

The work of this section is mostly to provide an initial orientation to devices and methods used later, so that little data analysis is required.

Experiment A-4 involves a comparison of the thermocouple with the mercury-in-glass thermometer from several standpoints, including "response time". The results obtained using the thermocouple will usually indicate a response time of from one to several seconds. However, the precise value depends strongly on the junction geometry and the materials used. For instance, a soldered junction may have quite a different response from one which is welded. Also, a junction which has been flattened out to a thin, wafer-like shape may respond more quickly to thermal transients than one having the shape of a rod. Because the exact conditions play such a strong role in the behavior, this topic is usually not dealt with to any great extent in the standard literature on thermocouples. Under optimal conditions, the response time may be as short as a few microseconds.

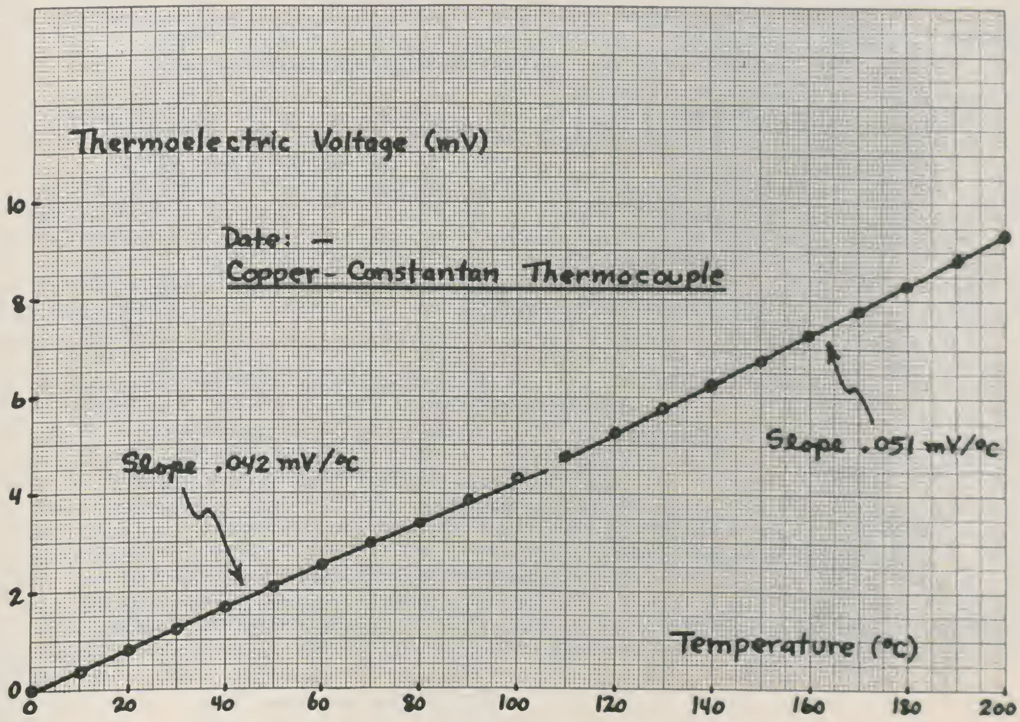
In the module, the student is instructed to plot a graph of thermocouple voltage versus temperature from the thermocouple calibration table. The figure on the following page shows such a calibration curve for a copper-constantan thermocouple, with the reference junction at 0°C. A straight line passing through the lowest temperature points (including the origin) begins to depart noticeably from the other points only above 100°C. The voltage at this tempera-

ture is 4.2mV, so the slope of the line is 4.2mV ÷ 100°C, or .042mV/°C. This gives the "thermoelectric power" α for the junction pair, as defined in the module.

More properly, the thermoelectric power can be defined as the actual slope of the calibration graph at any given point (corresponding to the derivative, dV/dT). As such, it is a temperature dependent quantity. From this standpoint, the parameter α is really the *average* thermoelectric power over the range 0-100°C. However, since the curve is essentially linear below 100°C the distinction is not important. Above 100°C the slope becomes quite different (more like .051mV/°C). That fact would have to be taken into account in accurate work.

Incidentally, as an example of the nonlinear behavior of thermocouples, this is not a very dramatic case. Other junction pairs, especially at much lower or higher temperatures, show curves which bend over considerably. In some cases they even pass through a maximum or minimum, so that the thermoelectric power changes sign.

The module assesses the advantages and disadvantages of thermocouples compared to resistance thermometers and thermistors. The point is made that thermistors require frequent recalibration. Since for this device, unlike the other two, the thermometric property (the resistance) is not linear with temperature, such a need may seem rather forbidding. In fact, however, it is easily accomplished,

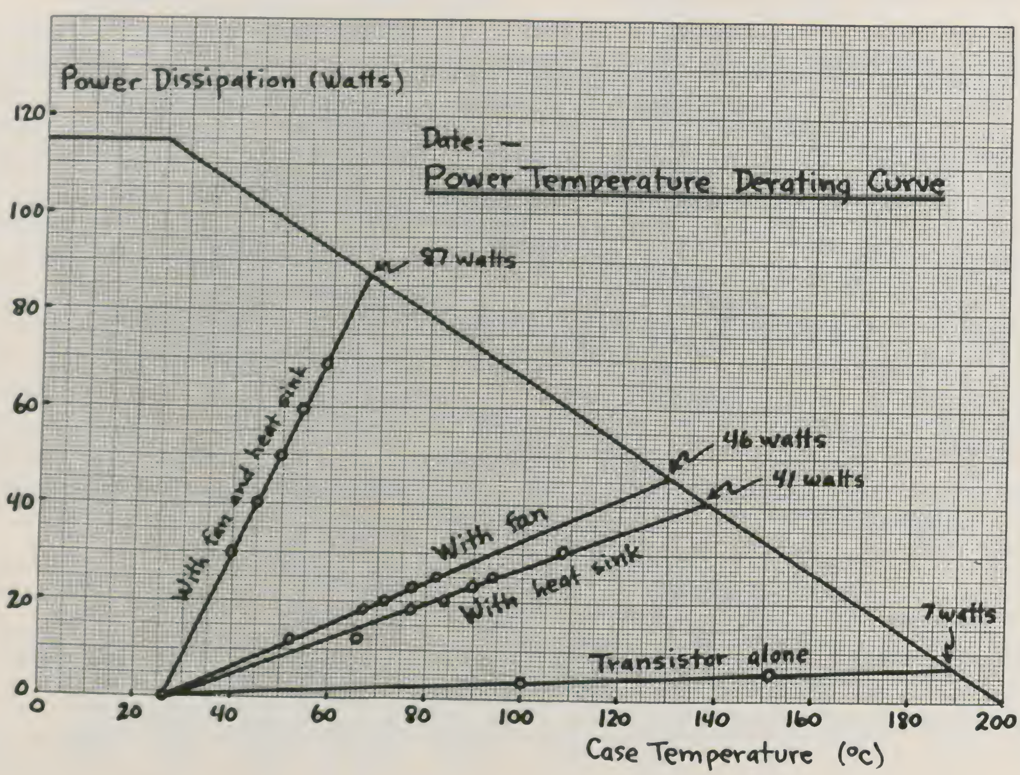


requiring merely a resistance check at any one temperature. The reason is that the calibration curve for a thermistor becomes quite accurately linear when log R is plotted versus T^{-1}. Thus log $R = \alpha + \beta T^{-1}$, and furthermore the constant β remains fixed for a given thermistor type. Only the constant α needs to be rechecked from time to time. (This point is more thoroughly discussed in the *Pressure Cooker* Module.)

SECTION B

The graph below summarizes results obtained in the four experiments of this section. The line sloping down to the right is the Power Temperature Derating Curve copied from the transistor specification sheet. The four other lines give the transistor case temperatures at various operating powers, measured under four different cooling conditions.

At zero power, the temperature is of course just the room temperature in any case. Thus, the four curves radiate from a single point at the lower left. At the other extreme, the place where any one curve meets the Derating Curve shows the maximum safe operating power under those particular conditions. For instance, with the transistor alone only 7 watts of power is safe. With the fan and heat sink, one can operate safely at 87 watts. Interestingly, for no



conditions tested was the safe dissipation as high as 115 watts, the "Total Device Dissipation" listed on the spec sheet. Obviously, the need for derating this figure under realistic circumstances is essential.

From ony one experimental line, we can calculate the case-air thermal resistance R_{ca} for that setup. This is just the inverse of the slope of the given line. For instance, with the transistor alone, the case temperature increases by 164°C (from 26°C to 190°C) when the power increases from zero to the maximum safe value, 7 watts. The thermal resistance is therefore:

$$R_{ca} = 164°C \div 7 \text{ watts}$$

$$= 23°C/\text{watt}.$$

With the heat sink and fan, of course, the thermal resistance is much smaller:

$$R_{ca} = 41°C \div 87 \text{ watts}$$

$$= 0.47°C/\text{watt}.$$

In order to increase the power to the full rated value, 115 watts, it would be necessary to lower the air temperature below 26°C. As noted in the module, this can be done with a small "thermoelectric refrigerator". Presumably one would also use a fan and heat sink to maintain R_{ca} as low as possible. The necessary air temperature T_a can be found as follows, using the value of thermal resistance calculated above.

The heat flow equation is $P = (T_c-T_a)/R_{ca}$, where P is the power and T_c is the appropriate case temperature. Thus $(T_c-T_a) = PR_{ca}$. We use $R_{ca} = 0.47°C/\text{watt}$ and set P = 115 watts, with the result:

$$(T_c-T_a) = (115W)(0.47°C/W)$$

$$= 54°C.$$

To find the value for T_a one must find T_c, which can be done by consulting the Derating Curve again. One notes that a dissipation of 115W is safe for any T_c below 25°C. There is, however, no advantage in going lower than this. Therefore one can assume $T_c = 25°C = -29°C$. This represents the highest possible air temperature which would still permit an operating power of 115W when using a fan and heat sink.

The transistor specification sheet lists the junction-case thermal resistance R_{jc}. This is determined from the sloping portion of the Power Temperature Derating Curve. When the case temperature increases by 100°C (say from 100°C to 200°C), the maximum safe power decreases by 66W (from 66W to zero). Therefore:

$$R_{jc} = 100°C + 66W$$

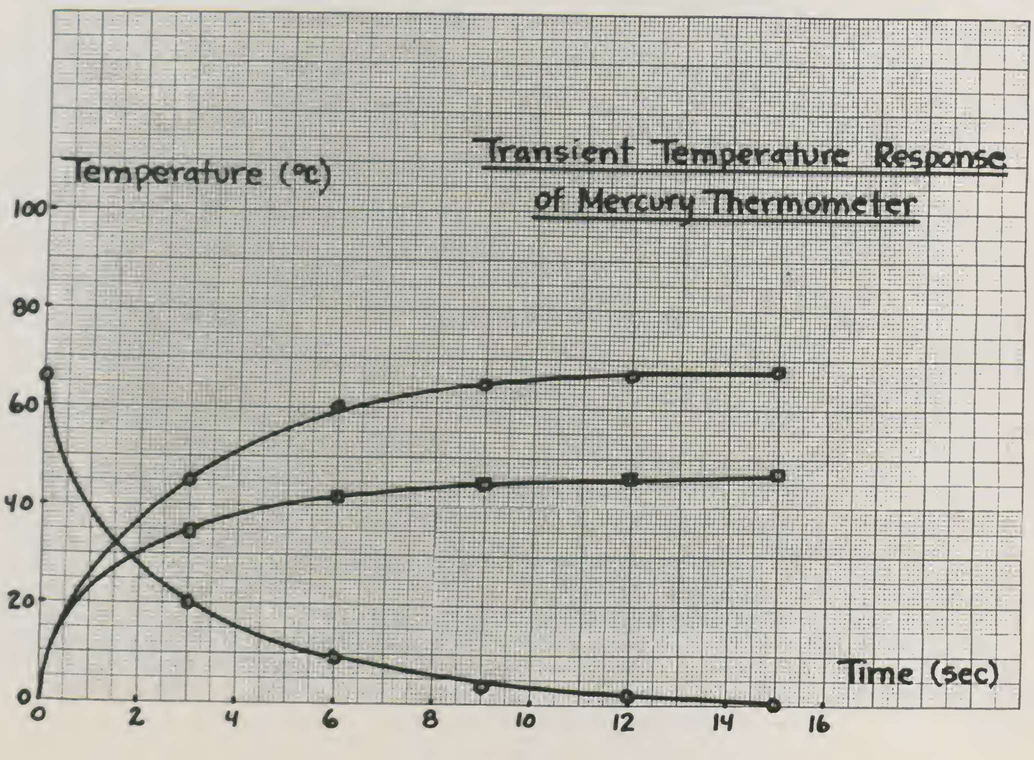
$$= 1.5°C/W.$$

SECTION C

The work here begins with a quick study of transients in a mercury-in-glass thermometer. The first graph below shows typical results, which by and large speak for themselves. The response to a step increase of temperature has been measured and plotted. Then the response was observed when the temperature was suddenly decreased to its original value. Finally, the response to a second, smaller temperature increase was observed.

At this stage no real analysis is called for. The warming and cooling curves for a given temperature step are seen to be mirror images. Furthermore, each is roughly exponential with a time constant of about 3 seconds. This is the time required for the response to come within 37% of its final value.

In the second experiment, data for thermal transients in a power transistor are taken. Typical results are shown in the next graph on the following page. First, temperature readings were taken at equally spaced time intervals after a power of 5.4 watts was switched on. Then the power was switched off and more readings were taken. Finally, the process was repeated using a power of 3.0 watts. In each case the early readings were spaced 15 seconds apart, because the initial temperature change was quite rigid. After the first minute it

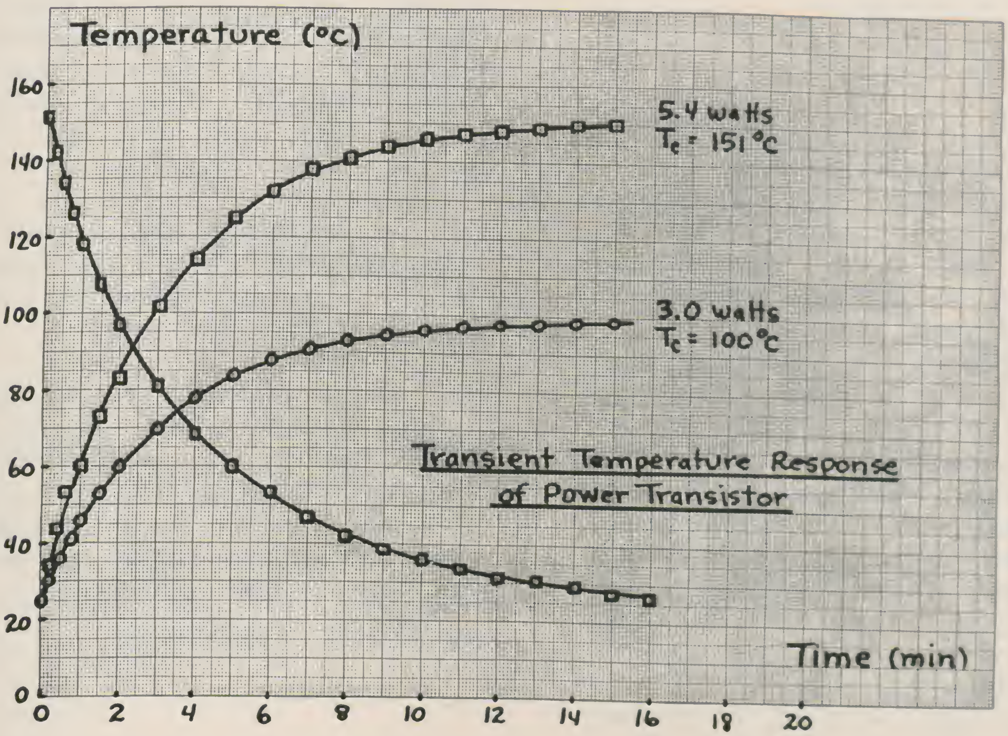


was sufficient to take readings at one minute intervals.

The qualitative response of the transistor is similar to that of the mercury thermometer, but the time constant is much longer. This can be determined by looking at any one of the various curves. For instance, for a power increase of 5.4 watts, the overall temperature change was 125°C (that is, 150°C - 25°C). Calculating 37% of this gives 46°C. The time required to go from 25°C to a temperature 46°C below the final temperature (150°C - 46°C = 104°C) was 3 minutes. This is one estimate for the time constant τ.

Another way of estimating τ is to start from any time on the warming curve. Find the total temperature change remaining from there, and then see what additional time was required to warm through all but 37% of that change. This additional time should also equal τ.

For instance, the warming curve for 5.4 watts of power shows a temperature of 125°C after 5 minutes. This is 25°C from the final temperature. Since 37% of 25°C is 9°C, we look for a temperature of 150°C - 9°C = 141°C on the curve. This occurred just 3 minutes later, as expected. The agreement with the previous value for τ, tends to confirm the belief that the warming is an exponential process. (A detailed verification of this can be accomplished by plotting the warming curve on semilog paper, to see if a



straight line is obtained. This is in fact the case.)

A third method for estimating τ would be to use the initial slope of a warming or cooling curve, as outlined in the module. However, slopes of exponential curves are different to judge accurately, so this is generally not as satisfactory as the other methods.

To relate the value of τ to the case-air thermal resistance, R_{ca}, we need C, the heat capacity of the transistor. The relation is $\tau = R_{ca}C$. In the previous section the value R_{ca}=23°C/watt. was obtained. To proceed further one can estimate C, as suggested in the module, and with it calculate the thermal time constant. Or, one can reverse the logic and use τ to calculate C. This gives:

$$C = \tau/R_{ca} = 180 \text{ sec} \div 23°\text{C/W}$$

$$= 7.8 \text{ joules/°C.}$$

This value agrees well with an estimate based on the fact that the transistor is mostly aluminum (specific heat: 0.88 J/g°C), and has a mass of about 10g (including the socket).

The final work of the section is to carry out similar transient measurements using a transistor plus heat sink. The results are qualitatively similar (and will not be shown here), but the response is *not* a simple exponential. This can be established by comparing the various estimates for τ and noting the lack of satisfactory agreement. A semilog plot of the response indicates that two separate time constants are involved in this case. The overall "rise time" (10% to 90% of total response) is about 10 minutes. The large value undoubtedly results from the large thermal capacity of the massive heat sink.

VII SOLUTIONS TO PROBLEMS

SECTION A

Questions

1. Put thermistor in water; connect to ohmmeter. Measure resistance at several different water temperatures (as determined using mercury-in-glass thermometer, for example). Can use ice water and boiling water for additional "fixed points". Plot R versus T; join points with smooth curve.

2. Simple "response time" experiment indicates, for thermocouple, thermal time constant roughly 1-2 sec. Thus: 0.1sec? (No.) 2 sec? (Yes, marginal.) 15 sec? (Yes, conservative.)

3. Response time of each thermometer is shorter in water than in air, because thermal contact is better in water.

4. a) "sensitivity" refers to the minimum detectable change in the reading of a measuring instrument; "accuracy" refers to the degree of agreement of the reading with the actual value of the quantity being measured.

b) Sensitivity.

Problems

1. a) $P = VI$

$V = 0.5W \div 1x10^{-3}A$
$= 500V$

b) $R = V/I = 500V \div 1x10^{-3}A$
$= 500k\Omega$.

2. a) 50°C: 99W
120°C: 53W
170°C: 21W

b) 12W: 184°C
40W: 140°C
116W: no safe temp.

3. 102°W allowable power.

$P = VI$, $I = P/V = 102W \div 40V$
$= 2.55A$.

4. a) $V=(0.0528mV/°C)(100°C)$
$= 5.28mV$.

b) $T=V/\alpha = 4mV \div 0.041mV/°C$
$= 1 \times 10^2 °C$.

c) $V = (0.063mV/°C)(900°C)$
$= 56.7mV$.

$R = V/I = 56.7x10^{-3}V \div 0.5A$
$= 0.113\Omega$

5. a) $T = V/\alpha = 2.5mV \div 0.063mV/°C$
$= 40°C$.
T is temp.diff., so temp. is 60°C.

b) From derating curve, 92W.

SECTION B

Questions

1. a) $R_f = (P_1-P_2)/\nu$
$= (200N/m^2) \div (15m/sec)$
$= 13\ Nsec/m^3$.

b) Twice R_f; one-quarter R_f.

2. a) $P_{cond} = (T_h-T_c)/R_{cond}$. If P_{cond} is fixed, and R_{cond} decreased, (T_h-T_c) must decrease.

b) If P_{cond} is *fixed* (not reasonable!), then (T_h-T_c) decreases from 25°C to 2.5°C. Thus T_h = 32.5°C.

c) Lower resistance, because evaporation carries away heat (by convection). Thus T_h lower.

d) Convection in air; conduction and convection in water.

Problems

1. $R = L/RA$
$= (0.2cm) \div (0.01W/cm°C)(75cm)^2$
$= 3.5 \times 10^{-3}W/°C$.

$P_{cond} = (T_h-T_c)/R_{cond}$
$= (30°C) \div (3.5x10^{-3} W/°C)$
$= 8.6kW$.

SECTION C

Questions

1. a) Because the thermal resistance from air to glass is greater.

b) The thermometer would still have a mass that takes time to heat up. The same is true of thermocouples, but the effect is less pronounced, since their mass is very small.

2. a) $\text{Input Power} = \text{Heating Power}$

$$VI = mc\,\frac{\Delta T}{\Delta t}$$

b) T would increase without limit.

c) $\frac{\Delta T}{\Delta t} = 0$; T does not change.

d) Refrigerator or freezer; oven; foam food container. Any real wall of a box will always have less than infinite thermal resistance.

3. The PR drop exists only when power is flowing into the mercury. The temperature of the mercury will rise steadily and become nearer and nearer to the temperature of the surroundings. Since the thermal resistance is much less in water, equilibrium between mercury and water will be reached relatively quickly.

Problems

1. $P = mc\,\frac{\Delta T}{\Delta t}$

$$\Delta t = \frac{mc\Delta T}{P} = \frac{(750\text{gm})(4.2\frac{\text{joules}}{\text{gm}\ ^\circ\text{C}})(80^\circ\text{C})}{1000\ \frac{\text{joules}}{\text{sec}}}$$

$= 252$ sec.

$= 4.2$ min.

Takes longer to heat, is some losses exit.

2. $\tau = RC$; Exponential decay is 95% completed in a time $T=3\tau$.

a) If $3\tau = 30$ min, then $\tau = 10$ min $= 600$ sec.

b) $\tau = RC$, $R=\tau/C$

$$= \frac{600\text{ sec}}{(500\text{gm})(4.2\frac{\text{joules}}{\text{gm}\ ^\circ\text{C}})}$$

$= .29^\circ$C/watt.

3. $T_f = T_{air} + RxVI$

$= 30^\circ\text{C} + (5^\circ\text{C/watt})(3\text{ watts})$

$= 45^\circ$C

4. a) $T_f - T_i$ (amount-to-go)= $120^\circ-20^\circ=100^\circ$C. Then $(100^\circ\text{C})(0.37)$ $=37^\circ$C. (This is the 38%-to-go value). Now $120^\circ-37^\circ=83^\circ$C x (temperature at 37%-to-go point). From graph, time corresponding to this is 0.8min= 48sec. This is the time constant. Initial slope gives similar value.

b) -

c) $R = \frac{T_f - T_{air}}{P} = \frac{120^\circ-20^\circ\text{C}}{5\text{ watts}}$

$= 20^\circ$C/watt

d) $\tau = RC$, $C = \tau/R$

$= 48\text{sec} \div (20^\circ\text{C/W})$

$= 2.4\text{J}/^\circ\text{C}$.

e) $C = mc$, $m = c/\tau$

$= (2.4\text{J}/^\circ\text{C}) \div (0.88\text{J/g}^\circ\text{C})$

$= 2.7$g.

f) $T_f = T_{air} + RP$

$= 20^\circ\text{C} + (20^\circ\text{C/W})(7\text{W})$

$= 160^\circ$C.

5. Yes, because 38%-to-go time is always 48 sec, for any "starting" time. Response time (99% completion of total change) is about 3 minutes. Rise time (10% to 90%) is about 1.8 min.

VIII POST TESTS

Test A

1) What are two advantages and two disadvantages of using a thermocouple to measure temperatures, in comparison to using a mercury-in-glass thermometer?

2) The thermoelectric power of a chromel-alumel thermocouple is 0.041 mV/°C. What is the temperature sensitivity when this thermocouple is used with a meter whose scale can be read to about 0.1 mV?

3) Suppose a certain thermocouple reading increases by 4.2 mV when one junction is removed from ice water and placed in boiling water. What is the approximate thermoelectric power?

4) If a power transistor uses a 12V supply and operates at a power level of 100W, what is the output current?

5) In using a power transistor, what is the practical significance of the "power temperature derating curve?"

6) What heat transfer mechanism makes it possible for the earth to receive energy from the sun?

7) What devices and instruments would you need to determine the maximum permissible operating power of a power transistor using a given heat sink and fan? (List as many as possible.)

8) In using electrical resistors, a voltage difference is required to make current flow. What is required to make heat flow in a "thermal" resistor?

9) Suppose that the power dissipation in a transistor is 5W when the case temperature is 140°C. The air temperature is 20°C. How great is the thermal resistance, R_{ca}?

10) In using an electric heater to heat a room, which heat transfer process is *least* important: convection; conduction (through the air), or radiation?

11) If the heat capacity of a transistor is about 3J/°C, how much heat is involved in warming the transistor to 200°C from room temperature (20°C)?

12) To what does the term "transient response" refer, when discussing the case temperature versus dissipation for a power transistor?

13) What common method is used to specify the rate of a *non*-exponential transient?

14) The thermal time constant for a power transistor with heat sink is 4.2 min. If the case temperature is 120°C when the power is switched off, what is the case temperature after 4.2 min?

(Hint: the air temperature is 20°C.)

15) What is the case-to-air thermal resistance, R_{ca}, for a transistor whose thermal time constant is τ = 3 min? The heat capacity equals 9J/°C.

Test B

1) What limitations determine the range of a mercury-in-glass thermometer? Consider the high and low temperature limits separately.

2) Suppose it is necessary to measure temperature using a thermocouple, with a sensitivity of about 0.2°C. A voltmeter is available whose sensitivity is 0.01 mV. What thermoelectric power is required?

3) If the thermoelectric power of a chromel-constantan thermocouple is 0.063 mV/°C, and if one junction is held at 0°C, what is the temperature of the other junction when the voltage reading is 2.1 mV?

4) It is desired to draw an output of 8.0A from a power transistor, while limiting the operating power to 70W. What should the supply voltage be?

5) What is the purpose of using a heat sink on a power transistor, in terms of the power temperature derating curve?

6) Which basic heat transfer mechanism is exploited when a fan is used for cooling?

7) By using a sufficiently effective fan, could the power dissipation of a power transistor be increased by any arbitrary level? Explain.

8) What is "thermal resistance?" Define as accurately as possible.

9) The specification sheet for a power transistor lists the junction-to-case thermal resistance, Θ_{jc}, as 1.52°C/W. What is the junction temperature when the case temperature is 20°C and the dissipation is 130W?

10) Usually home heating systems bring energy from the furnace to the various rooms by convection: Explain briefly.

11) What quantity determines the energy required to raise the temperature of an object by one degree?

12) In measurements of the transient response of a transistor's temperature to a given change of power, which takes longer, the transient decay or the transient growth? Can you give a reason why?

13) How is the term "rise time" of a transient defined?

14) When a transistor is switched off, the case cools to 60°C after one time constant, τ = 3 min. What will the temperature be after 3 more minutes, if the air temperature is 20°C?

15) The thermal time constant of a power transistor and heat sink is 3 min., and the thermal resistance to the air is 2°C/W. What is the heat capacity of the setup?

SOLUTIONS TO POST-TESTS

Test A

1) Advantages: Good thermal contact, small heat capacity, quick response time, large range.
Also, electrical signal for easy read out.

Disadvantages: Requires electronic accessories and reference junction temperature control.

2) 0.4°C.

3) .042 mV/°C.

4) 8.3A.

5) Specifies maximum safe power at operating temperature.

6) Radiation.

7) Transistor; 12V power supply; battery and potentiometer (also limiting resistor) for base current; ammeter; thermos; ice. (Could use alternative thermometer.)

8) Temperature difference.

9) 24°C/W.

10) Conduction.

11) 540J.

12) How rapidly the temperature approaches a new value after the dissipation is suddenly changed.

13) "Rise time" is time required for change to increase from 10% to 90% of its final value. ("Decay time" also used.)

14) 37°C + 20°C = 57°C.

15) 20°C/W.

Test B

1) Freezing of mercury; melting temperature of glass.

2) 0.05 mV/°C.

3) 33°C.

4) 8.8V.

5) To increase the safe operating power by decreasing the case temperature.

6) Convection.

7. No. Fan can at best reduce case temperature to room temperature.

8) Temperature difference ÷ heat flow.

9) 178°C.

10) Furnace heats a fluid (air, water, or steam). Fluid moves to rooms through ducts or pipes, where heat is deposited.

11) Heat capacity.

12) Same time required, since same thermal resistance determines both rise time and decay time.

13) Time required for change to increase from 10% to 90% of final value.

14) 35°C.

15) 90J/°C.

OPTIONAL LAB PROBLEMS

Section A

1) Given the necessary equipment, determine the approximate thermoelectric power of a thermocouple.

2) Given a preset power transistor circuit, including output ammeter, determine the operating power using appropriate voltage and current measurements.

Section B

1) Given prewired power transistor and thermocouple setups, determine the steady state case temperature of the transistor for a given operating power.

2) By making appropriate measurements of temperature and power, determine the case-to-air thermal resistance of a power transistor operating in a preset circuit.

Section C

1) Given ice water, boiling water, and a stop watch, determine the thermal rise time of a mercury-in-glass thermometer.

OPTIONAL GRAPHING PROBLEMS

Section A

1) Given the voltage-temperature plot for a thermocouple, find the temperature corresponding to a certain voltage reading.

2) From a plot of voltage versus temperature for a thermocouple, determine the approximate thermoelectric power.

Section B

1) Given the power temperature derating curve for a power transistor, and one data point representing the case temperature at a given dissipation with (for example) heat sink and fan, determine the maximum safe dissipation under those conditions.

2) Given the power temperature derating curve for a power transistor, from a knowledge of room temperature and the maximum safe dissipation under given conditions, predict the case temperature at some smaller power.

Section C

1) Given a plot of temperature versus time for the cooling of a cup of water, determine the thermal time constant.

2) Given the graph of a non-exponential transient, find its rise time.

IX LIST OF APPARATUS

Section A

Transistor
Transistor socket
Screws (9) (Eyelets may be substituted for 5)
Fan or blower with line cord, 4- to 5-in. blade diameter, 100-cfm capacity
Thermocouple wire, 36-in. copper-constantan with enamel/glass insulation
Insulated cup or thermos, approx. 250 ml, styrofoam
Thermometer, -10°C to +110°C
Wire, #18 AWG, solid tinned brass
Battery, 6V
Power supply, 6V DC (15A or less, capable of delivering 40W)
Ammeter, 0 to 5 A DC
Dual banana plug (black, 3/4-in. centers)
Amplifier, operational, with external input/output and gain and offset controls
Wire leads, #20 AWG standard, cut 12 in. long (3)
Banana plugs, black, solderless type (3)
Banana jacks (3 red, 8 black)
Potentiometer (10kΩ, e W ohmite)
Resistor (47Ω), 1/2W ohmite
Circuit board (plain masonite or phenolic board, 5 x 8 in.)
Rubber feet or bumpers (1/2 in. diameter, 1/4 in. tall)
Meter, 0 to 100 μA DC (either 2-1/2 or 3-1/2 in. meter movement)
Solder, rosin core
Crushed ice (250 g)

Section B

Same as for Section A, minus thermometer and plus:
Heat sink for TO-3 transistor case

Section C

Same as for Section A, plus:
Watch or clock with second hand
Glass beaker, 250 ml

OPTIONAL DEMONSTRATION AIDS

A simple and interesting way of showing the importance of emissivity for radiation is the Sutton Demo N. H-157.

Sutton, Demonstration Experiments in Physics, McGraw-Hill, 1938.

INSTRUCTOR'S MANUAL FOR THE PRESSURE COOKER

CONTENTS

I INTRODUCTION

The overall goal of this module is to introduce and examine a variety of ideas concerning the familiar *phases* of matter (solid; liquid; gas). Special attention is paid to ways of defining and measuring the *energy* needed for changing the state of matter - either through warming or cooling a single phase (heat capacity; specific heat), or through phase transformations (heat of melting; heat of vaporization; etc.). The ordinary concepts of temperature and pressure are examined and refined, and the meaning of *absolute temperature* is conveyed. In this connection, some insight is provided into the usefulness and limitations of the *general gas law*, which relates the parameters T and P for a "perfect" gas to the volume and number of molecules (or moles).

The examples and experiments in the module center around the properties of water - the only substance which is familiar to everyone in all three of its phases. With only a few simple modifications, the household pressure cooker provides a convenient "laboratory" for observing basic aspects of water's behavior, such as the dependence of the boiling point on pressure. This leads to a greater understanding of practical topics like the weather (relative humidity; dew point), refrigeration and air conditioning, and the "energy budget" for home heating by hot water or steam.

Besides the knowledge the student will gain concerning fundamental thermal properties of matter, in the course of his work he will become better acquainted with some devices and methods for technical measurements. For example, he will use a Bourdon gauge for measuring the pressure both above and below atmospheric (and incidentally, he will learn the distinction between absolute pressure and gauge pressure). More importantly, he will encounter some problems of practical thermometry, and will discover the advantages of the *thermistor* used as a thermometer. In this way he will be introduced to the need for the *calibration* of such an instrument.

II SPECIAL PREREQUISITES

There are no special physics prerequisites for this module.

However, students should be able to read meters and to determine the mass of an object using a common balance scale.

III TABLE OF CONTENTS OF THE MODULE

IV GOALS

The objectives of this module are discussed at the beginning of the module.

V DISCUSSION OF ACTIVITIES

The module is divided into three parts.

SECTION A

The main experiment here is a quantitative observation of the changes in water caused by adding energy, progressing from the ice phase through the liquid to steam. Energy is added to the water by an immersion heater, which was chosen as a source because the power can be precisely controlled and the energy input accurately measured. *The immersion heater should never be turned on unless it is immersed in water.* Otherwise it may easily overheat and melt.

In this part, the water is contained in a wide-mouthed vacuum bottle (not a pressure cooker) to minimize energy losses by heat flow. A thermistor is chosen to monitor the temperature because it and the accompanying ohmmeter are technologically interesting, and experience with them is likely to be useful to the student later. A mercury-in-glass thermometer or a thermocouple would also serve, but would be less convenient to use.

As a preliminary step to the main experiment, the thermistor must be calibrated. This is straightforward. However, the student should realize that *it is advisable to check the calibration occasionally*. The resistance value at a given temperature may change by several percent, especially after pro-

longed or extreme heating. This corresponds to a potential temperature error of several degrees.

The calorimetric experiment itself is simple and straightforward, but the student should work carefully to minimize errors. One source of error is heat flow to the surroundings rather than to the water. Thus, when the weighing of the ice is begun, this should be carried out quickly to minimize melting. As suggested in the text, precooling the vacuum bottle is helpful. Capping the bottle whenever possible also reduces heat leaks. Of course, if the cap is on when a weighing is made, this fact should be noted.

The warming experiment can probably best be carried out by two students working as a team. A large, easy-to-read timer or stop watch should be placed near to the ohmmeter. When the ohmmeter scale is changed, the meter should be re-zeroed.

Finally, it may be necessary to emphasize that what is desired here is not a very accurate "calorimetric" determination of specific heat, latent heats, etc., which will agree closely with published values. Instead, the purpose is for the student to participate in a semi-quantitative experience, using simple and familiar items of equipment, which will be accurate enough to make clear the meaning and relevance of physical principles for ordinary events.

SECTION B

The main emphasis here is on an investigation of the gas phase of matter, using the pressure cooker as a gas tight container. Again, a thermistor is used for temperature measurement, and air is used as the gas under study. In this part, precise control of energy input is not required, so the container and thus the gas are simply heated with an electric hot plate. The air is heated to about 160°C with the cooker unsealed, and then allowed to cool down with the cooker sealed. The gas pressure is measured as a function of temperature, and this important proportionality is established.

A particularly rewarding outcome of the pressure-temperature measurement arises from the p-T graph. This graph can be extrapolated to zero pressure and a value obtained for "absolute zero". The instructor must be careful to avoid the implication that this extrapolation is rigorous evidence for the existence of an absolute zero. The procedure does give a pretty good value for zero Kelvin, but the real evidence comes from thermodynamic considerations - most notably the theory of heat engines, as expressed by the Carnot cycle.

In this part, probably the most serious difficulty is air leakage. This is most likely to occur at the seal between the cover and the pressure cooker body. As mentioned in the text, a light

coating of grease on the rubber gasket is essential. Rough handling by students can put nicks and dents on the sealing surfaces, so careful handling is advised. If the surfaces become badly dented, some of the roughness can be removed by "sandpapering". Fasten a large sheet of fine emery paper to a smooth *flat*(!) table, then rub the damaged surface on this with a circular motion. Of course, you should go through the leak test, as described in the text, to be sure that the leaks are not occurring at the fittings.

Warn the students of the danger of going above 160°C. The solder on the thermistor leads will melt, of course, and also the rubber gasket is not apt to hold up well at much higher temperatures. Mention also the possible dangers in working with pressures *above* atmospheric: a pressure much above 15psig exceeds the manufacturer's safety rating.

In greasing the rubber stopper and the gasket to promote a good pressure seal, do *not* use vaseline, as this may deteriorate rubber. Use a commercial vacuum grease or, more simply, cooking oil. Note that the rubber stopper used as the electrical feed-through must be inserted in the right way. The smaller tapered end should point toward lower pressure, so that pressure will tend to force the fitting into place and prevent any leaks.

SECTION C

This section is concerned with a detailed look at one important phase change -- the vaporization (or condensation) of water. The technological applications are briefly discussed, ranging from gas storage and steam heat to the use of humidity determinations in meteorology. The concept of the phase diagram is developed further to explain such phenomena as sublimation and critical point. The idea of vapor pressure is introduced, and the boiling point curve on a phase diagram is seen to be given by the curve of vapor pressure as a function of temperature. Relative humidity and dew point are discussed in terms of vapor pressure of water in the atmosphere.

In the experiment to measure the vapor pressure-temperature curve for water, the pressure inside the cooker is always greater then atmospheric. Therefore some special precautions must be observed. Put in the electrical feed-through so the thicker part is on the inside; this makes a better seal, as discussed previously.

Never seal the pressure release hole with a rubber stopper in this experiment. A dangerous pressure could build up quickly. Use only the pressure regulating weight, and be sure the hole is clear.

Also, never attempt to open the cover with any overpressure inside. Always

remove the regulator weight first to release all pressure. *Never remove the weight until the water has cooled thoroughly to below 100°C.* Suddenly releasing the pressure might cause the water to boil violently and shoot out a jet of hot water or steam.

The temperature to be measured here is the *equilibrium* temperature where the liquid and vapor exist together. Students should try to place the thermistor as close as possible to the liquid-vapor interface. Particularly avoid placing the thermistor near the cover or the bottom. If the hot plate can be powered through a Variac (or other adjustable voltage source), the rate of increase of temperature and pressure can be decreased if desired. This makes it easier to approach a condition of equilibrium throughout the experiment.

In the dew point experiment, the exact nature of the cup is not critical. The cup, however, should be a pretty good heat conductor, so that the outer surface is at the same temperature as the water. The condensation is easier to see if the surface is smooth with a metallic or grey finish.

VI SAMPLE DATA

SECTION A

The graph on the following page labeled "Warming of Water" shows typical data obtained for Experiment A-2. The slanted line segment drawn thru the points for intermediate times leads to a calculation of the specific heat capacity of water. The *slope* of this segment is the only feature which is relevant for the calculations, and we can (for convenience) determine this by noting that the segment increases from 0°C to 100°C in a time interval of 15 min. With these values, the calculation proceeds as follows:

$$\text{Energy Supplied} = \text{Power} \times \text{Time} = (145\,\text{watts}) \times (900\,\text{sec}) = 1.3 \times 10^5\,\text{joules}$$

$$\text{Specific Heat Capacity} = \frac{\text{energy supplied}}{\text{mass} \times \text{temp. change}} = \frac{1.3 \times 10^5\,\text{joules}}{(240.5\,\text{g})(100°\text{C})} = 5.4\,\text{joules}/\text{g}°\text{C}$$

The energy unit here can be converted from joules to calories by multiplying by the ratio 1 cal/4.2 joules. The result is C=1.3cal/g°C which is to be compared with the accepted value of 1.0cal/g°C. A 30% discrepancy is certainly acceptable in such a crude experiment, especially since the purpose is to exemplify and clarify the basic thermal behavior of real systems, *not* to "measure" certain material constants (for which other more careful methods are obviously required).

It is not too difficult to understand the discrepancy, since the value obtain-

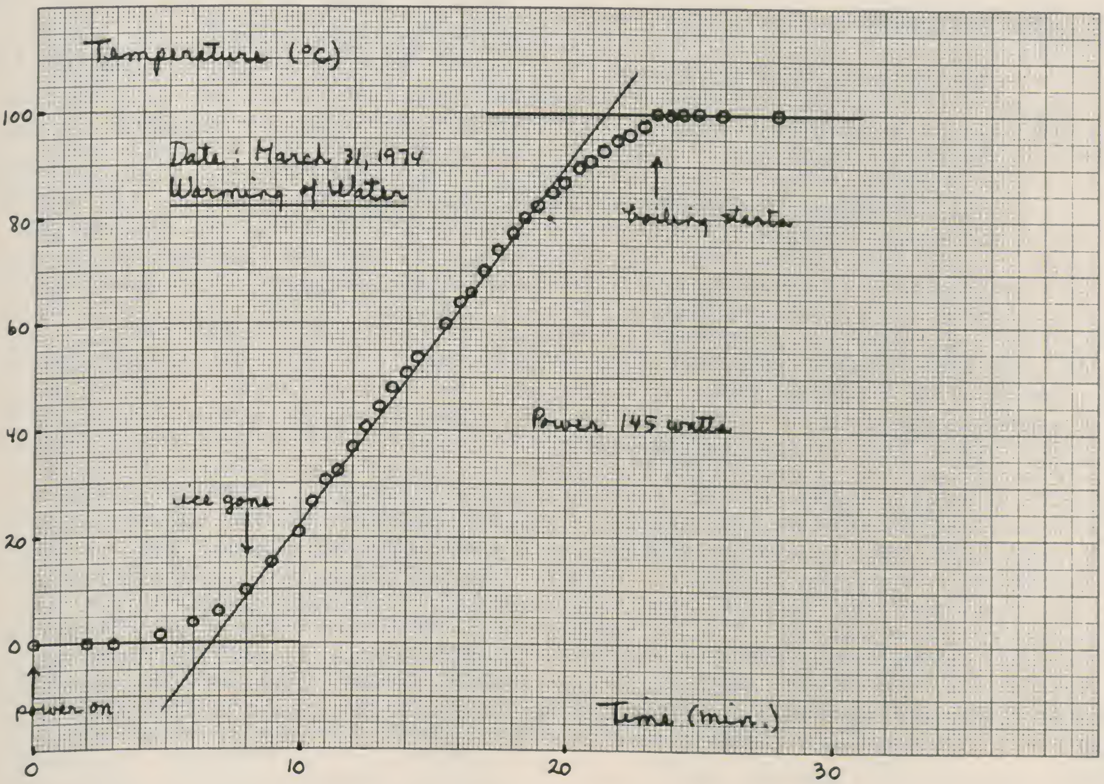
ed for C is larger than it should be. This means that more energy was consumed than was required to warm the water, and one must suppose that the excess went to warming the thermos and the surrounding air, etc. It may be instructive to consider with the students some ways of minimizing these "errors". Implementing some of the suggested improvements might furnish a worthwhile extra credit task, or even a classroom demonstration. Possible approaches to the problem include these:

1) Apply a correction based on the thermal capacity of the container. This means estimating (or measuring, if it can be removed) the mass of the inner glass container, multiplying this by the specific heat capacity of glass, and subtracting the result from the total energy input. A limitation of this method is the probable lack of equilibrium between the thermos and the water, due to the poor thermal time constant involved.

2) Use a styrofoam cup or other container having a lower heat capacity than the glass.

3) Reduce heat losses to the outside by thermally insulating the system. A glass wool or styrofoam cover may help most.

4) Maintain the surroundings always at nearly



the same temperature as the water. (One simple technique might be to immerse the vacuum bottle in a water bath, slowly heated so its temperature remains close to that of the system.) This is the most sophisticated approach, and while it may seem a trifle impractical here, it is the method of choice in the most careful work. The general name for such a technique is *adiabatic calorimetry*.

Turning now to a calculation of the latent heat of melting, we find from the note on the graph that the last ice disappeared 8 min. after the heater was first turned on. The initial masses of ice and water were 156g and 84g, respectively (total: 240g). Thus:

$$\text{Energy Supplied} = Q = Pt$$

$$= (145w) \times (480sec)$$

$$\text{Latent Heat} = \ell_m = \frac{Q}{mass}$$

$$= \frac{7.0 \times 10^4 \text{ joules}}{156g}$$

$$= 4.5 \times 10^2 \text{joules/g}.$$

Once again converting from joules to calories, we obtain $\ell_m = 1.1 \times 10^2$cal/g, while the accepted value is 80cal/g. The 30% discrepancy here is in the same direction as before, meaning that some part of the energy was not used for melting the ice. Again we can assume that there were losses to the surrounding air, etc. However, in this case we can observe a significant additional source of error by looking more closely at the warming curve itself. We see that the temperature reading at t=8 min was not in fact 0 °C, but rather 10°C. Thus, when the last ice disappeared, the bulk of the water had already been raised to 10°C, which required (for a mass of about 240g) essentially 10^4joules of energy. This figure represents about a seventh of the total energy supplied to the system up to that time, leaving less for the phase transformation itself.

The calculation of the latent heat of vaporization proceeds in a similar fashion, using the fact that when the heater was turned off after 38 minutes, it was found that 54.1 grams of water had boiled away. Since the note on the graph indicates that boiling began at about 24 minutes, we find $\ell_v = 5.4 \times 10^2$cal/g, which is rather surprisingly almost exactly the accepted value. The greatly improved accuracy in this case is not merely accidental, but comes about mostly because ℓ_m is so large compared to the possible heat losses.

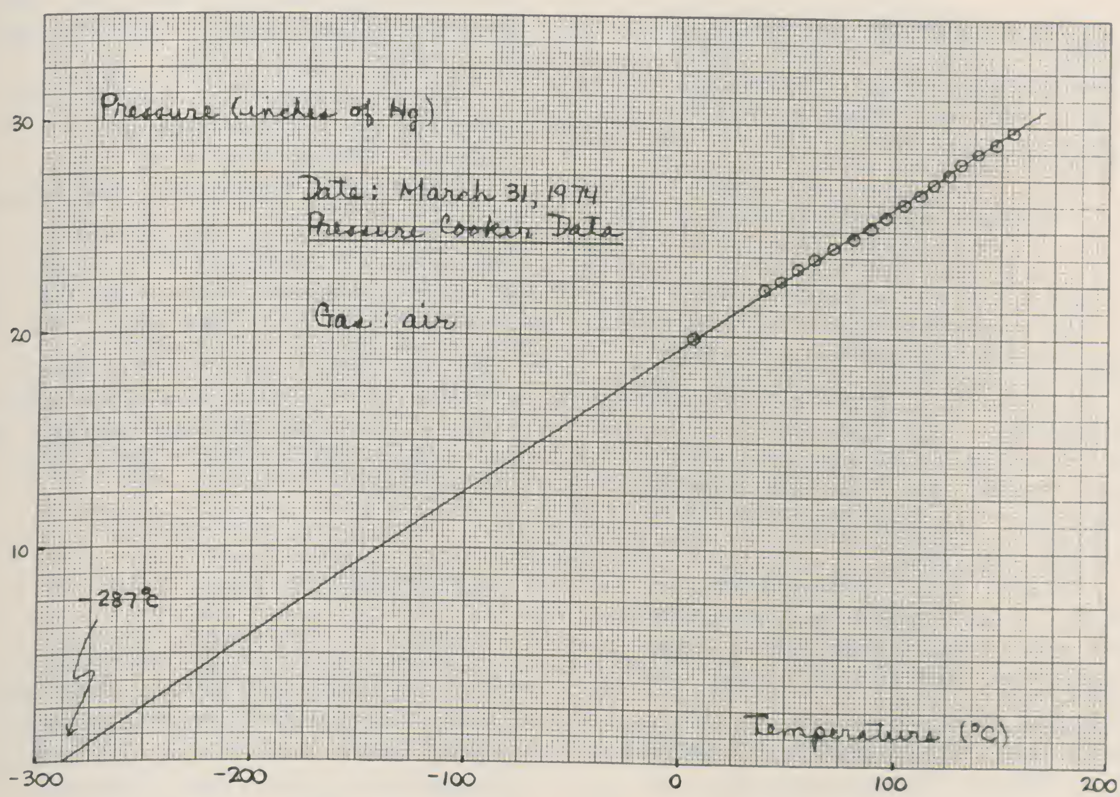
SECTION B

The graph shown on the following page labelled "Pressure Cooker Data" shows that a respectable value for absolute zero temperature can be gotten with this experimental procedure. One can obtain a number of pressure values below atmospheric, corres-

ponding to temperatures between 160°C and room temperature, and with reasonable care the points will fall quite accurately on a straight line. If the points do not follow a straight line, but curve downward bery noticeably toward the left, it is a sign that the cooker leaked. There is no choice but to search for the leaks (as described in the module), seal them, and repeat the measurements.

The data analysis here is straightforward, although one should note that extrapolation of even a well determined line over a great range can introduce large errors. It is often helpful to hold up the graph paper so that one can sight along it at a shallow angle to see the trend of the points. A difference of 10°C either way from the ideal value -273°C for the intercept at P = 0 is certainly not unexpected.

Of course the pressure used in the gas law (and in the graph) must be the absolute pressure, whereas the gauge pressure readings represent only the differences below atmospheric. In converting these readings, you must add the ambient atmospheric pressure, which may be taken as 30in.Hg or 14.7 psi if (and *only* if) the experiment is done near sea level. At other altitudes you must determine the barometric pressure at your location. This is *not neces-*



sarily the reading of a weather barometer or a TV weather forecaster's value. Such values may be "reduced to sea level", in which case they are not the actual local pressure but represent what the pressure *would be* if the measurement were at sea level under the same atmospheric conditions. You can get an uncorrected value by measuring your own mercury manometer or from an uncorrected aneroid barometer.

If you have only a weather forecaster's barometric pressure, you can "uncorrect" it in a simple way. Just *subtract* one inch of mercury for each 1000 feet of your altitude above sea level. As an equation:

$$B = B_{SL} - (1in)(h\ in.1000ft.).$$

For example if you are at Denver and the sea level pressure for your location is 30.1 in.Hg, the actual pressure is:

$$B = 30.1-(1in)(5)$$
$$= 25.1\ in.Hg.$$

This connection is only approximate, but is compatible with the accuracy of the experiment. If you wish to make a more precise correction, refer to "Reduction of Barometer to Sea Level" in the CRC Tables.

There is a possible variation of this experiment that could be done as a demonstration or tried with interested students: one can repeat the measurements with a gas other than air, to verify that the gas law is indeed general for all gases. If dry ice is available, the cooker can easily be filled with CO_2 just by letting a piece of dry ice sublime in it. Close the cover, but leave the pressure release hole open until the CO_2 is all sublimed. You can find when this occurs by putting your finger over the hole: if you feel pressure building up, CO_2 is still subliming.

It would also be instructive to try the experiment with other gases such as helium or argon. Use inert or non-flammable gases only! Avoid hydrogen, acetylene, methane, etc. Pure oxygen should also be avoided since it can promote violent combustion.

Helium and argon, for example, are available at laboratory supply houses in aersol-type cans. Argon, being more dense than air, tends to displace air more completely from the container. Feed the gas in through the pressure release fitting; leave the feed-through hole open to allow air to escape. It is hard to judge when all the air has been flushed out, but this is not really a serious issue. The important point is to get a different mixture of gases

SECTION C

The previous comments about gauge pressure conversions to absolute pressures apply here as well. The graph included, labelled "Vapor Pressure of Water" shows

again that quite good results can be obtained with this simple arrangement.

VII SOLUTIONS TO PROBLEMS

SECTION A

Questions

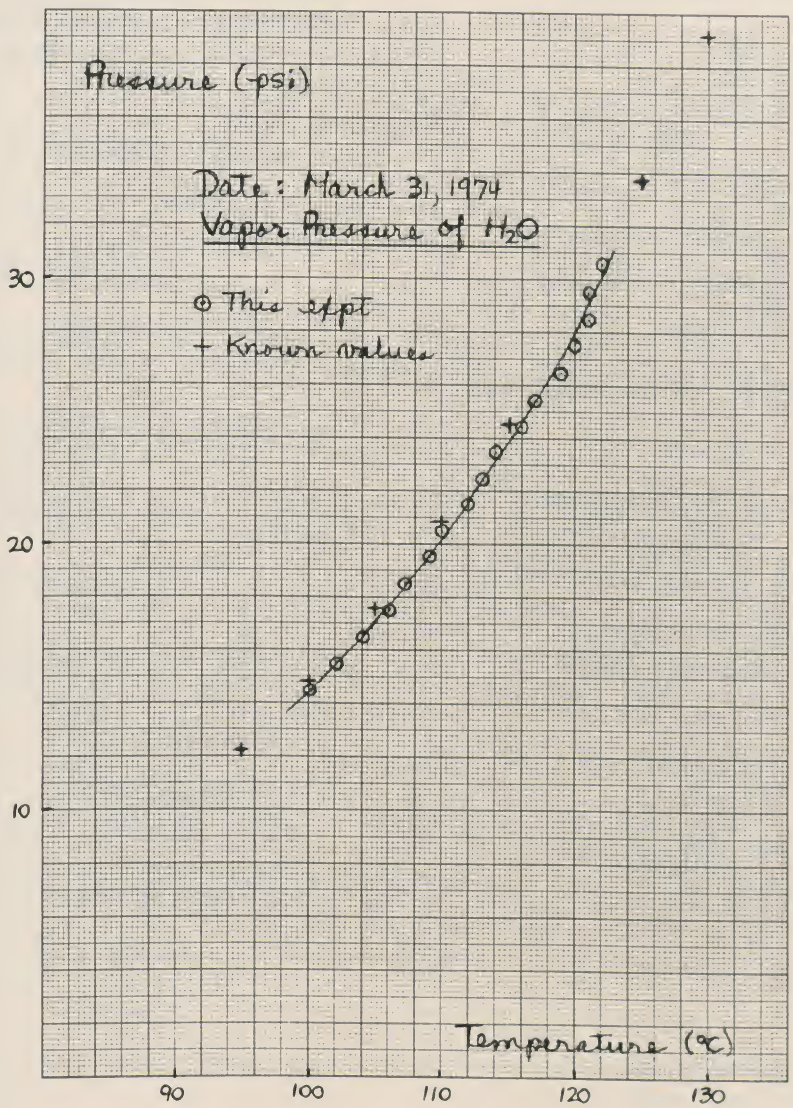
1. (C) watt is not an energy unit, it is a power unit.

2. Mg: 651°C; 1107°C.
   Cs: 28.5°C; 670°C.

3. Boiling began; all the energy input went into the phase change.

4. Power is the time *rate* at which energy is used, transferred, or dissipated.

5. Specific heat capacity of a substance is energy required per unit mass to pro-



duce a one-degree temperature change.

Latent heat of a substance is energy required per unit mass to produce a phase change - melting or vaporization.

Problems

1. $Q = mC\Delta t = (100gm)(0.092\ cal/gm°C)(880°C)$

$= 8100\ cal.$

2. Ammonia: L_v=327cal/gm.

$Q = mL_v = (10gm)(327cal/gm)$
$= 3270\ cal.$

3. $1\ hp = 550ft.lb/sec \times 60sec/min$

$= 33{,}000ft.lb/min$

work = power x time

$= (750w)(120sec)$

$= 90{,}000$ joules

4. $1\ kw\text{-}hr = (250/1000kw)(t)$

$t = 4\ hr.$

5. $Q_1 = mC\Delta t = (250gm)(1\ cal/gm°C)(80°C)$

$= 20{,}000cal.$

$Q_2 = mL_v = (250gm)(540\ cal/gm)$

$= 135{,}000\ cal.$

$Q_{tot} = 155{,}000\ cal \times 4.19$ joules/cal.

$= 649{,}000$ joules

SECTION B

Problems

1. $P \alpha T$

$$P_2 = P_1 \frac{T_2}{T_1} = (2200psi)\left(\frac{339°K}{293°K}\right)$$

$= 2550\ psi.$

Leaving full SCUBA tanks in car trunks is not recommended. The temperature and pressure can climb high enough so the pressure may approach the bursting pressure. Internal rust may weaken a tank so its bursting pressure is reduced.

2. $PV = NkT,\ N = PV/kT$

$$= \frac{(9atm)(1.01x10^5 \frac{nt}{m^2 atm})(0.1m^3)}{(1.38x10^{-23} \frac{joules}{°K})\ (293°K)}$$

$= 2.25 \times 10^{25}$ molecules

3. $V \alpha T,\ V \alpha 1/P$

$$V_2 = V_1 \left(\frac{T_2}{T_1}\right)\left(\frac{P_1}{P_2}\right)$$

$$= (15cm^3)\left(\frac{293°K}{277°K}\right)\left(\frac{5atm}{1atm}\right)$$

$= 79.3\ cm^3.$

4. $-182.97°C$

$\underline{+273.16°C}$

$90.19°K$

$$T_F = \frac{9}{5}(T_C) + 32°F$$

$= 754 + 32$

$= 786°F$

$T_R = T_F + 460°K$

$= 870 + 460$

$= 1246°K$

5. $T_C = \frac{5}{9}(98.6°F - 32°F)$

$= 37°C$

$T_K = 37° + 273°$

$= 310°K$

$T_C = T_K - 273° = 6000° - 273°$

$= 5727°C$

$T_F = \frac{9}{5}C + 32°F$

$= \frac{9}{5}(5730°) + 32°F$

$= 10,308 + 32$

$= 10,341°F$

6. 29.9in.Hg-12.5in.Hg
= 17.4 in.Hg

$\frac{17.4\text{in.Hg}}{29.9\text{in.Hg/atm}} = 0.58\text{atm}$

$(0.58\text{atm})(1.01\text{x}10^5 \frac{\text{nt}}{\text{m}^2\text{-atm}})$

$= 0.59\text{x}10^5 \frac{\text{nt}}{\text{m}^2}$

7. $\left(\frac{132\ \text{ft}}{33\ \frac{\text{ft}}{\text{atm}}}\right) \quad \left(15\ \frac{\text{psi}}{\text{atm}}\right)$

$= 60$ psig

$60\text{psi} + 15\text{psi} = 75\text{psia}$

$F = PA = (75\frac{\text{lb}}{\text{in}^2})(10\text{in}^2)$

$= 750$ lb.

8. $P = F/A$ = Weight/Area

Weight $= F = PA$

$= (30\frac{\text{lb}}{\text{in}^2})(0.05\text{in}^2)$

$= 1.5\text{lb}$

9. $P = F/A = 2500\text{lb}/15\text{in}^2$

$= 167\text{psi}$

10. $P_1 = NkT_1/V_1$

$P_2 = NkT_2/V_2$

$\frac{P_2}{P_1} = \frac{NkT_2/V_2}{NkT_1/V_1}$

$P_2 = P_1\left(\frac{T_2}{T_1}\right)\left(\frac{V_1}{V_2}\right)$

$= (12\frac{\text{lb}}{\text{in}^2})(\frac{573°K}{343°K})(9.5)$

$= 190$ psia

SECTION C

Questions

1. Fog indicates 47°F is dew point and relative humidity closely 100%.

2. 240mm.Hg BP:70°C

3. 640mm.Hg BP:95°C

4. $\frac{640\text{mm.Hg}}{760\text{mm.Hg/atm}}(14.7\frac{\text{psi}}{\text{atm}})$
= 12.4 psi.

a) 15psi + 12.4psi = 27.4psia

b) 119°C

c) No, Temperature is lower than the sea level value.

5. Freezing coils are usually about 0°F = -18°C, which is below the triple point. Hence, water vapor in the air condenses directly to the solid phase.

6. The combustion raised the air temperature above the dew point so the fog (droplets of liquid water) vaporized to invisible water vapor.

7. Pressure decreases as depth decreases, allowing volume to increase.

8. When air is nearly saturated with water vapor (high RH), the evaporation rate is slow. Yes, moisture in cloths freezes, then sublimes.

9. Evaporation reduces the temperature of the water.

Problems

1. a) 72°F

b) 20mm.Hg

c) 20mm.Hg

d) 32mm.Hg

e) $RH = \frac{20}{32}$

$= 62.5\%$

VIII POST-TESTS

Test A

1) Can you "heat" a substance without raising its temperature? If so, given an example. If not, why not?

(Hint: Recall your own experiment.)

2) When using a thermistor as a thermometer in your experiments, a "calibration" was needed. In your own words, define the term "calibration".

3) An electrical toaster uses 1100 watts of power when plugged into a 110 volt outlet. What is the resistance of the heating element?

4) With constant power applied, a certain mass of water is first warmed from 0°C to 100°C and then completely boiled away. Which process takes longer? How many times longer?

(Hint: The latent heat of vaporization of water is 540cal/g.)

5) Starting with a known mass of ice at 0°C, you measure the time required to completely transform it to water at 0°C. What additional information is needed in order to calculate the latent heat for this process? What is the process called?

6) An automobile tire is inflated to a pressure of 25psig. Then, as a result of some driving, the absolute pressure in the tire increases by 10%. What is the new gauge pressure?

(Hint: Use P_{atmos} = 15psi.)

7) A 110 lb. woman is standing in high heeled shoes. If her weight rests totally on one heel, and the area of a heel is 0.2 in^2, what is the pressure on the floor at that point?

8) The introduction of the "absolute" scale of temperature simplifies the P-T relation for a gas at constant volume. In what way is this relation simplified?

9) In the Fahrenheit temperature scale, ice melts at 32°F

and water boils at 212°F. How many Fahrenheit degrees equal one Centigrade degrees?

10) By what factor does the density of air increase if the temperature drops from 300°K to 294°K while the pressure stays the same?

(Hint: Density is proportional to N/V, where N is the number of molecules in a volume V.)

11) The "vaporization curve" for water separates two different phase regions in the P-T diagram. What are these regions?

12) When a dish of water at room temperature is placed in a vacuum jar, and the jar is pumped down increasingly below atmospheric pressure, the water finally begins to boil. Why is this?

(Hint: Consider the form of the vaporization curve as a function of P and T.)

13) On cold days in winter, when your home must be furnace heated, the air inside may be more dry than that of the most dry desert. Why? Explain in detail.

14) Why is the "triple point" of water useful in accurately calibrating a thermometer. Why is it better than the melting point in this respect?

15) The rate of change of equilibrium vapor pressure with temperature for water near 100°C is about 0.56psi/°C. What is the boiling temperature of water in Denver, Colorado, where because of the altitude, the atmospheric pressure is 2.3psi less then at sea level?

Test B

1) Explain the statement: "Boiling can be thought of as a cooling process".

2) On the "slide rule" type scale used for calibrating your thermistor, the temperature and resistance readings increased in *opposite* directions. What physical property of the thermistor made this necessary?

3) The immersion heater is most commonly used for boiling water for instant coffee or tea. When plugged into an ordinary electrical outlet, the heater's voltage is 110 volts (average value). Suppose the resistance is 50Ω. What is the heater power under these conditions?

4) How long will it take to bring half a quart of water (m=500g) to a boil, starting from room temperature (20°C), if the heating rate is 200 watts?

(Hint: The specific heat capacity of water equals 4.2joules/g°C.)

5) What information is needed to calculate the heat capacity of a given substance, if the specific heat is known?

6) By sucking hard, the pressure in the lungs can be reduced to 1.5psig (vac.). What absolute pressure does this represent?

(Hint: Use P_{atmos} = 14.7psi.)

7) An explosion creates a momentary increase in the air pressure. If this "overpressure" equals 0.4psi, what is the resulting net force on the wall of a building 20ft high and 30ft wide?

8) The pressure of a constant volume of gas is measured

at various temperatures near room temperature. A linear relation is observed: $P = a + bT$, where T is expressed in the centrigrade scale. What is the best estimate for "absolute zero" temperature in terms of the constants a and b?

9) The relation between Fahrenheit and centigrade temperature readings is given by this equation:

$$T_c = \frac{5}{9} (T_F - 32).$$

In the centigrade scale, "absolute zero" equals -273°C. What does this equal in the Fahrenheit scale?

10) What fraction of the air molecules in a room must leave, if the temperature increases from 17°C to 27°C while the pressure remains constant?

(Hint: "Absolute zero" temperature equals -273°C.)

11) A certain curve in the P-T diagram for water separates the solid and liquid regions. What is this curve called?

12) It takes longer to "hard boil" an egg at high altitudes than at sea level, where atmospheric pressure is greater. Why is this?

(Hint: Consider the form of the vaporization curve as a function of T and P.)

13) On cold days, the windows in your home may get wet on the inside. Why? Explain in detail.

14) The vaporization curve for water does not extend above a certain point in the P-T phase diagram. What is this point called? What separates the liquid and vapor regions above this point?

15) Why do foods cook more rapidly when boiled in a pressure cooker than when boiled in an open pot?

SOLUTIONS TO POST-TESTS

Test A

1) Yes. Boiling.

2) -

3) 11Ω.

4) Boiling, 5.4 times longer.

5) Power; melting.

6) 29psig.

7) 550psi.

8) P is proportional to T.

9) 9/5.

10) 2% increase.

11) Liquid and vapor.

12) Vapor pressure exceeds external pressure.

13) Relative humidity of air decreases when air is warmed without adding more water. This is because equilibrium vapor vapor pressure is greater, higher temperature.

14) Unique temperature for coexistence of three phases, by contrast melting tem-

perature varies slightly with atmospheric pressure.

15) 96°C.

Test B

1) Vapor escaping continually carries away latent heat from liquid. Otherwise, heat added would cause temperature to rise.

2) Resistance decreases at T increases.

3) 242watts.

4) 840sec.

5) Mass.

6) 13.2psi.

7) 34,560lb.

8) -a/b.

9) -459°F.

10) 1/30.

11) Melting curve.

12) Boiling temperature is less, since boiling occurs when vapor pressure exceeds atmospheric.

13) Window temperature is less then dew point.

14) Critical point; nothing (no distinction).

15) Boiling temperature higher.

OPTIONAL LAB PROBLEMS

Section A

1) Given the necessary equipment, calibrate a thermistor for use as a thermometer, with room temperature as the fixed point.

2) Given a resistor of unknown value, make appropriate measurements and calculations to determine what voltage would be required for producing a specified electrical power.

3) Given a beam balance and two thermos bottles, one containing some water, find how long it would take to warm the water by 10°C using 150 watts of power.

Section B

1) Read a barometer, and convert the reading to absolute pressure.

2) Read the pressure gauge on a pre-sealed pressure cooker, and convert the reading to absolute pressure.

Section C

1) Measure the relative humidity of the atmosphere by comparing the readings of wet and dry bulb thermometers.

2) Determine the atmospheric dew point using a metal cup, some water, and ice.

OPTIONAL GRAPHING PROBLEMS

Section A

1) Given a warming curve at constant power for a certain mass of water, calculate the specific heat capacity.

2) Given a thermistor calibration curve plotted on semilog graph paper, recalibrate the thermistor using one new fixed point.

3) Calibrate a thermistor, using two or three given fixed points and a sheet of semilog graph paper.

Section B

1) Determine absolute zero temperature from a graph showing the P-T relation for a given mass of gas at fixed volume.

Section C

1) Given the vapor pressure-temperature curve for water, from the relative humidity of the atmosphere find the dew point.

2) Find the boiling temperature of water at a certain altitude, given graphs showing the vapor pressure-temperature relation for water as well as the curve of atmospheric pressure versus elevation above sea level.

IX LIST OF APPARATUS

Section A

Thermistor, 1kΩ + 10%
Ohmmeter, multi-range (capable of measuring 0 to 10kΩ)
Immersion heater (single cup hot water heater), 115V/250W
Vacuum bottle, 2-in. diameter
Trip scale balance, 500-g capacity, 1-g sensitivity
Set of metric weights (1 g to 1 kg)
Variable autotransformer, 0 to 120 V, 10.0 A
Flexible wire leads, 24 in. long, terminating with either banana plugs or alligator clips on both ends (2)
Watch or clock with second hand
Crushed ice (250 g)

Section B

Thermistor, 1kΩ + 10%
Compound pressure gauge, 2-1/2-in. face, 30 in. Hg to 30 psi with recalibrateable dial
Pipe tee, brass, 1 in. x 1-1/4 in.
Bushing, reducer, brass, 1/4 in. to 1/8 in. (2)
Nipple, brass, 1 in. x 1/8 in.
Pressure cooker, 4-qt. (including pressure regulator, vent pipe, and sealing ring)
Rubber stopper, size 00, with 2 holes drilled through and copper wire inserted through each
Rubber stopper, size 4, partial hole drilled through center

Ohmmeter, multi-range (capable of measuring 0 to 10kΩ)
Flexible wire leads, 24 in. long, terminating with either banana plugs or alligator clips on both ends (2)
Paint brush, 1/2 in. wide
Soap or detergent
Pipe joint sealing tape, 1/2 in. wide
Rubber bulb pump, double valve pressure bulb
Rubber tubing, 12 in., amber latex, 3/16-in. ID, 3/32-in. wall
Vacuum grease
Metal cup (shiny aluminum)

Section C
Thermistor, 1kΩ + 10%
Compound pressure gauge, 2-1/2-in. face, 30 in. Hg to 30 psi with recalibrateable dial
Pipe tee, brass, 1 in. x 1-1/4 in.
Bushing, reducer, brass, 1/4 in. to 1/8 in. (2)
Nipple, brass, 1 in. x 1/8 in.
Ohmmeter, multi-range (capable of measuring 0 to 10kΩ)
Flexible wire leads, 24 in. long, terminating with either banana plugs or alligator clips on both ends (2)
Pressure cooker, 4 qt. (including pressure regulator, vent pipe, and sealing ring)
Rubber stopper, size 00, with 2 holes drilled through and copper wire inserted through each
Paint brush, 1/2 in. wide
Soap or detergent
Pipe joint sealing tape, 1/2 in. wide
Vacuum grease

OPTIONAL DEMONSTRATION AIDS

16-mm Sound Film

1. "Behavior of Gases," by L. Grodzins (PSSC film series)

Film Loops

1. "Boyle's Law."
2. "Finding Absolute Zero."

Both of the above are by Herbert and Shamos.

CONTENTS

I INTRODUCTION

This module has three main aims. First, the module conveys essential aspects of geometrical optics in the familiar context of an ordinary slide projector. Material covered includes such items as the use of ray diagrams to locate images, differences between real and virtual images, the "Universal Lens Rule" relating object and image positions, and so on.

Second, the module shows the broad applicability of optics by discussing a variety of other devices, in addition to the slide projector, which can be understood on a similar basis. In particular, it is shown that many devices are in essence "projectors" even though they go by different names and perform different functions. These devices include the camera, the microscope, the telescope, and even the human eye.

Third, the module suggests the fundamental basis of optics and some of its limitations by including a limited discussion of wave theory. For instance, the theoretical meaning of "rays" in terms of the motion of wave fronts is introduced, and this meaning is related to the formation and manipulation of practical rays in the laboratory. The basic "diffraction limit" which determines the minimum spreading of practical rays is mentioned, and the student can see this operating by a simple experiment with the slide projector.

Unlike most of the modules in the Physics of Technology series, the Slide Projector is divided into only two sections. This means that the work is meant to be completed in two weeks instead of the usual three. There are two reasons for this difference. First, many instructors will not wish to devote more than two weeks to what is sometimes regarded as a minor, albeit important and interesting, aspect of introductory physics. Second, the shorter form of the module means that instructors who do wish to pursue optics further can do so along two alternative paths.

One path is to examine more deeply the technical aspects of geometrical optics itself, such as applications to "thick" lenses and complicated lens systems. This can be accomplished by following the Projector with, for example, the Binoculars module. A second possible route is to follow the Projector with a module such as the Spectrophotometer, which uses optics as a tool to study the spectral properties of light. This in turn leads to numerous applications in the area of materials science. As is well known, spectrophotometers find wide use in medicine, industry, etc., so that their study affords an especially effective approach to elements of applied modern physics.

One additional feature of the Projector module deserves mention. This concerns the lack of any special equipment required for its use, other than the projector itself. In most cases, instructors will already have access to a projector which can be employed without modification, such as the standard "Carousel" projector depicted in the text. The experiments will not in any way damage the projector, since the only manipulations

involved are the usual ones of focusing, removing the lens barrel, examining the bulb, etc. Besides the projector, only minor items are needed, which are either readily available as such or can be easily fabricated by the instructor or students from available materials (black masking tape, razor blades, 2" x 2" microscope slides, etc.). Thus, the experiments in the module can be implemented with minimal trouble and expense. Furthermore, this will avoid some of the contrived appearance of standard introductory optics apparatus.

II SPECIAL PREREQUISITES

There are no special prerequisites for this module, except that for the Physics of Technology series as a whole: high school algebra.

III TABLE OF CONTENTS OF THE MODULE

IV GOALS

The objectives of the Slide Projector module have been included at the begining of the module.

V DISCUSSION OF ACTIVITIES

The module is divided into two Sections, each representing approximately one week's study. It assumes that approximately three class hours and two lab hours will be devoted to each section. A recommended scheduling of class and lab activities, and content

of class periods, is as follows:

First Class Period

This should orient the student to the topics that will be covered in the section and to the experiments that will be performed. It should include background material, for example a short film about the topic, and a discussion of the lab experiments and apparatus that will be used.

Laboratory Session

The laboratory experiments should be done before the week's final two class sessions. They generally can be done in a two-hour lab period, though slower-working students may take somewhat longer.

Second Class Period

This should discuss the laboratory activities and the data taken. The students should be helped in graphing and analyzing their results and in understanding the behavior in terms of the underlying physical laws or principles. If the optional experiments were not done by the students, they can be done here as demonstrations. Problems and questions can be assigned at this time.

Third Class Period

This should continue the discussion of the physics underlying the device behavior. The assigned Questions and Problems can also be discussed. It is often a good idea to end this class with a short 20-minute quiz on the section's work.

The following are specific notes relating to each section.

SECTION A

The work of this section is relatively straightforward and should pose no great difficulty. Experiment A-1 especially is quite simple, and should be completed in about 15 minutes. The essential point is to accurately locate the "optic center" of the projection lens, since subsequent work depends on that. In Experiment A-2, the object distance and image distance must both be measured from the optic center. If this is done properly, a very persuasive experimental determination of the Lens Rule, relating $\underline{d}_O$ and $\underline{d}_I$ to the focal length $\underline{f}$, is made possible. For some students, the work up to this point may constitute a review of material studied previously. In that case Experiments A-1 and A-2 can be gone through especially quickly. However, good data here are worth getting in any case, because the graphical extension of the lens rule to virtual images ("negative" image distances) is then much more convincing.

Experiment A-3 uses the "parallax" method for locating the position of a virtual image. Probably, not many students will be familiar with this procedure, and more time should be allotted for it. A little practice may be required before one can easily view both the image *through* the lens and the reference line *over* the lens with the same eye, while moving the line of sight back and forth slightly to observe the parallax motion. There is limited space between the end of the lens barrel and the focal plane, and the object in this case (an upright pin) must be located in that region. Therefore it may be difficult to get more than four or five distinct data points, but this will suffice to illustrate nicely the general behavior.

NOTE: Since the object distance, $\underline{d}_O$, in Experiment A-3 is small ($0 < \underline{d}_O \leq \underline{f}$), it is especially important to measure accurately *from the optic center* of the lens. Otherwise, the later graphical construction showing the Universal Lens Rule may be somewhat unsatisfactory.

The data analysis of Section A is aimed primarily at a graphical demonstration of the lens rule, $\underline{d}_O^{-1} + \underline{d}_I^{-1}$

$= \underline{f}^{-1}$. The graphing work itself is quite simple, but the instructor should make certain that two essential algebraic steps required for a complete understanding are emphasized. They are: (1) the inferring of a particular linear relation between $\underline{d}_O^{-1}$ and $\underline{d}_I^{-1}$ from the straight line obtained when one variable is plotted against the other; and (2) the smooth joining of the graphs for real and virtual images by the "trick" of taking virtual image distances as negative. The fact to be stressed in connection with (2) is that the negative sign for $\underline{d}_I$ is not a matter of logical necessity; rather, it is a convention adopted to simplify the form of the "law" which has been determined.

Some additional discussion of the relation between the usual "Gaussian" form of the lens rule (the form emphasized in the module) and the equivalent "Newtonian" form may be worthwhile. The equivalency breaks down for thick lenses, where there is not a single optic center with respect to which $\underline{d}_O$ and $\underline{d}_I$ can be measured. The Binoculars module goes into this matter in further detail, and it is shown that the Newtonian expression retains its usefulness under more general circumstances.

SECTION B

The work of this section is devoted to the practice and theory of ray tracing. First, in Experiment B-1, the operational meaning of "object point" and "image point" and the joining of these "conjugate points" by rays are briefly examined, using the projector and a slide image on a screen. Then in Experiment B-2 some experience is gained in forming, collimating, and focusing bundles of rays using the projector as a light source. This leads to a quantitative study, in Experiments B-3 and B-4, of the reflection and refraction of individual rays. From the data obtained, the law of reflection and the law of refraction (Snell's Law) are deduced. The index of refraction of water is determined. In optional experiments, the phenomena of dispersion and total internal reflection are investigated.

It should be remarked that the ray tracing work of these experiments could be accomplished slightly more efficiently using apparatus designed especially for the purpose, and commercially available. As an example, the traditional "Hartl optical disk", used with a prepared ray source, makes a measurement of refraction in special flat glass or plastic "lenses" extremely straightforward. On the other hand, using the projector to obtain similar results turns out to be not much more difficult in practice. Moreover, this has the great advantage that what is taking place will seem to many students less far removed from everyday circumstances.

In the module it is pointed out that a ray path is not ordinarily visible. To make it visible, it is necessary to place fine dust, smoke, or the like in the path. This scatters some of the light out of the original direction and into the eye. In the Experiments of Section B, what is actually done for measurements is to make the rays skim across a flat sheet of white paper, as in the Hartl disk. However, the use of smoke is well suited for demonstration purposes, since ray patterns can be easily viewed in three dimensions.

A convenient source of smoke for this purpose is incense (although a cigarette works about as well). One good way to proceed is to procure a section of glass or Plexiglas tubing about 18 in. long, and at least 3 in. in diameter. If the ends are capped with Saran wrap held by rubber bands, this will retain sufficient smoke to reveal rays inside the tube for one or two hours at least. The rays will enter an end without noticeable distortion if the Saran wrap is stretched tight. They can then be viewed by looking in through the side of the tube. A darkened room makes

the viewing easier.

NOTE: It is worthwhile to prepare a tube with smoke, as described, for students to "play" with during Experiment B-2. This will permit a vivid initial impression of the collimated rays from the projector, and it will reveal dramatically what happens when such parallel rays pass through a positive or negative lens.

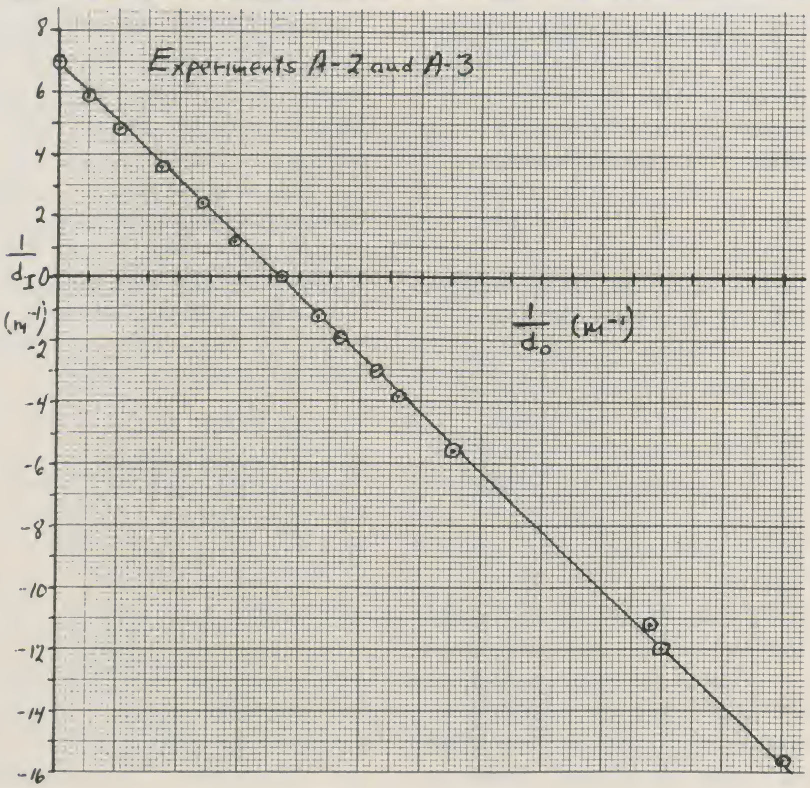
The discussion following the experiments in Section B begins with a brief analysis showing why the focal length of a spherical mirror is one-half the radius of curvature. This is probably the simplest case of practical importance in which one can derive a focal length from the laws of optics. Therefore, it may be worth going through the derivation briefly in one of the lectures. As the module also indicates, the focal length decreases for rays far from the axis (spherical aberrations), and this should be emphasized.

Later in the discussion ("How Lenses Work"), the concept of the Fresnel lens is introduced. It is possible to obtain--e.g., from Edmund Scientific Co. --large, high quality Fresnel lenses at moderate cost. These are virtually indestructible, and make interesting conversation pieces to hand around a classroom for examination during a lecture.

VI SAMPLE DATA

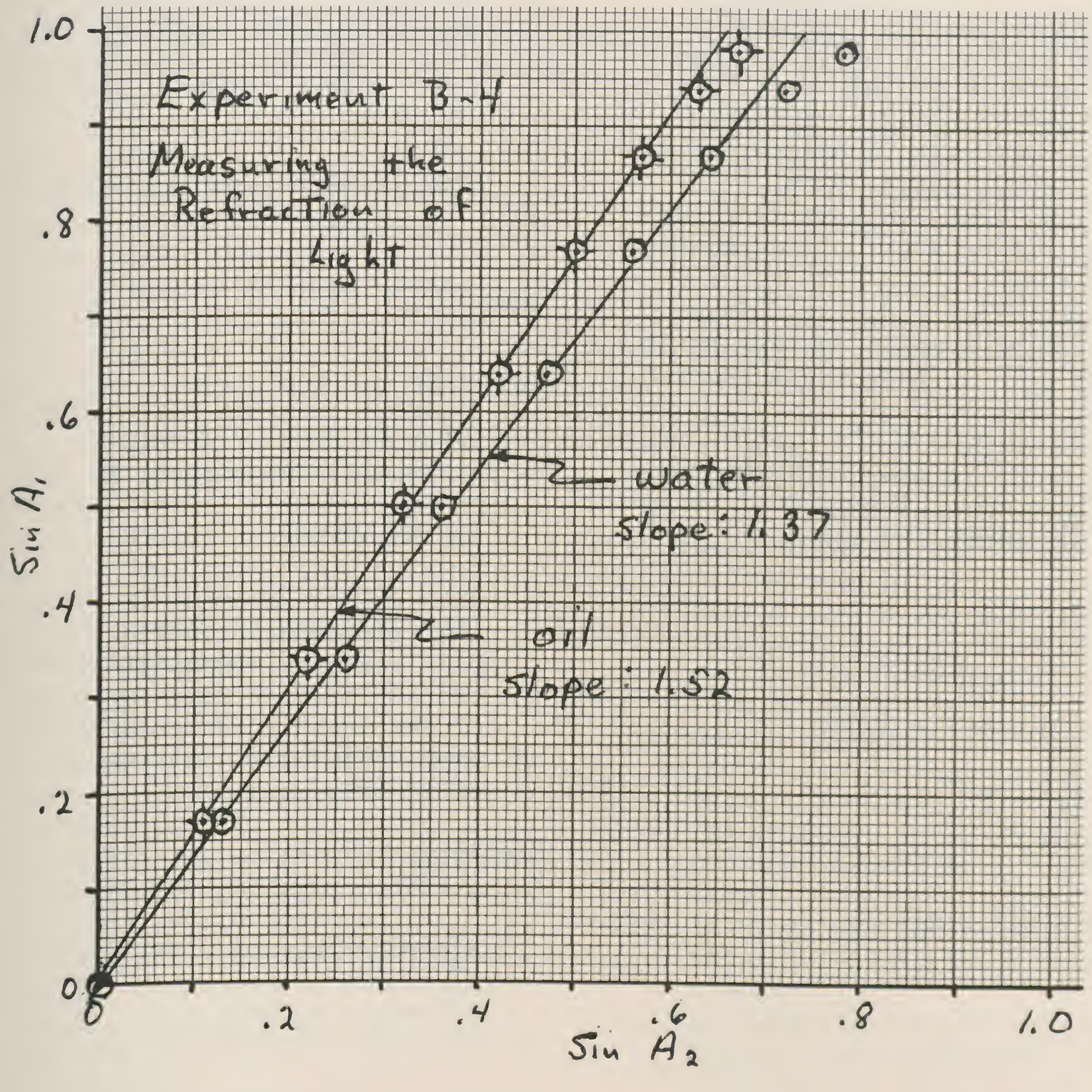
SECTION A

Experiments A-2 and A-3. Determining Image Distances and Locating Virtual Images. A schematic version of the graph obtained from this work is shown as Figure 36 in the module. Figure 1 below shows actual data plotted in similar fashion. These data were gotten using a Kodak Carousel Slide Projector lens, of focal length 5 in. Note that the units of inverse distance in the graph are m^{-1}, so that the straight line intercept on each axis gives the lens power in diopters (7.9D).



Experiment B-4. Measuring The Refraction Of Light. Again, a schematic version of the desired graph is given in the module as Figure 61. Figure 2 below shows two actual curves obtained using the method detailed in the Procedure. One of the curves is for water, giving an index of refraction 1.37. This, of course, is really the "relative index" between air and water (called $\underline{N_{aw}}$ in the discussion). However, since the absolute index for air is essentially unity ($\underline{n_a}$ = 1.003), and since the absolute index for water is $\underline{n_w} = \underline{N_{aw}} \times \underline{n_a}$, it is true that $\underline{n_w} \approx \underline{N_{aw}}$ within the experimental accuracy. On the other hand, the distinction is important to recognize in principle, and this is emphasized in the discussion.

The second set of data shown in Figure 2 pertains to light machine oil. Here the index is found to be $\underline{n_o} \approx \underline{N_{ao}}$ = 1.52. This is quite close to the value for water, but the difference shows up very clearly in the graph. Most common liquids have refractive indexes lying in roughly the same range.



VII SOLUTIONS TO QUESTIONS AND PROBLEMS

SECTION A

Questions

1. According to the lens rule, the image distance approaches a limit ($d_I \approx f$) as the object distance approaches infinity. However, as the object distance approaches f, the image distance increases without limit. The "limit of accomodation" is finally exceeded.
2. Similarities: real image; positive lens; focusing. Distances: image outside versus inside; "internal" versus "external" light source; "transparent" versus "opaque" projector.
3. Increase; increasing f-number means decreasing aperture, limiting light reaching film.
4. Positive lens can make rays converge (if $d_O > f$), while negative lens cannot.
5. Magnification = $d_I \div d_O$. Thus increasing m means decreasing d_O. Since $d_O \approx f$, this means shorter focal length.
6. No; since $d_t^{-1} = f^{-1} - d_O^{-1}$, if f is negative both terms on right are negative. Thus d must be also, so image is virtual.

Problems

1. $f^{-1} = d_O^{-1} + d_I^{-1}$

   $= 6.25\text{m}^{-1} + 2.08\text{m}^{-1}$

   $= 8.33\text{m}^{-1}$

   Thus: $f = 0.12\text{m}$

2. $d_O^{-1} = f^{-1} - d_I^{-1}$

   $= 0.5\ \text{in}^{-1} - (-0.1\text{m}^{-1})$

   $= 0.6\ \text{in}^{-1}$

   Thus: $d_O = 1.67$ in

3. $m = d_I \div d_O$

   $= \dfrac{10 \text{ in}}{1.67 \text{ in}}$

   $= 6$

4. $f = P^{-1}$

   $= 0.5$ m

5. $P = 0.6\ (r_1^{-1} - r_2^{-1})$

   $= 0.6\ (3.3\text{m}^{-1} + 3.3\text{m}^{-1})$

   $= 4\text{D}$

6. When d_O is very large, $d_I \approx f$. Thus f is 40mm = .04m in this case. When d_O = 1.5m, find $d_I^{-1} = f^{-1} - d_O^{-1} = 25\text{m}^{-1} - 0.67\text{m}^{-1} = 24.33\text{m}^{-1}$.

   Thus: film to lens distance $= d_I \approx 41\text{mm}$

SECTION B

Questions

1. Behavior of chief rays shows that image is totally inverted.
2. Since rays can be made to converge to a point, "real" images can be formed.
3. -
4. Rays in lab: created by "collimating"; minimum thickness ("diffraction limit"); unavoidable spreading. Rays in theory: not "created" by any means (always defined by wave motion); no thickness; no spreading.

Problems

1. $n_1 \sin A_1 = n_2 \sin A_2$ and

   $n_2 \sin A_2 = n_3 \sin A_3$, so

   $n_1 \sin A_1 = n_3 \sin A_3$

2. -

VIII POST-TESTS

Test I

1. It is desired to use a certain positive lense as a magnifying glass. Should the object be located:
   a) at the focal length?
   b) beyond the focal length?
   c) within the focal length?
2. If eyeglasses have a power of -10D, what is the focal length of the lenses?
3. An object is located 10cm from a lens of focal length 4cm. What is the image distance?
4. In problem 3, is the image real or virtual? erect or inverted?
5. A slide image is projected on a screen 50 feet from the lens. The focal length is 6 in. How great is the magnification?
6. When using a camera on a cloudy day, should the *f*-number be larger or smaller than on a sunny day? Why?
7. If two lenses of focal length 10cm each are placed in contact and used as a single "lens combination", what is *f* for the combination? (Hint: Consider the lens power.)
8. What is meant by the term "collimation"?
9. From the standpoint of the Universal Lens Rule, what is the principal difference between a real and a virtual image?
10. Considering the fact that light consists of waves, what is the true meaning of a "ray"?
11. Why does the "chief ray" pass through a thin lens without being bent at all?
12. State the law of reflection. Draw a sketch to indicate how the various angles are defined.
13. A light ray goes from air into glass. Measurements show that $\sin \Theta_1 = 0.50$ and $\sin \Theta_2 = 0.86$. What is the relative index of refraction?
14. What is the meaning of "absolute index of refraction" (as compared to "relative" index of refraction)?
15. The index of refraction of one medium is $N_1 = 1.6$, while that of a second is $N_2 = 1.2$. What is the relative index of refraction N_{12}?

Test II

1. In terms of the lens rule, describe the "accommodation" of human vision.
2. The diameter of an eyeball is about 2.5 cm. Approximately, how great is the power of the lens?
3. When can a negative lens form a real image? Why?
4. In a photographic enlarger, the film negative is placed 10 in from the lens, while the printed image appears 15 in from the lens. What is the lens focal length?
5. In the previous problem, how great is the magnification?
6. If a screen is moved closer to the projector, should the lens be moved toward or away from the slide, to refocus? Explain.
7. What must you do to use a positive lens as a magnifying glass?
8. If a card with a small hole in it is placed as close as possible in front of a slide projector lens, what changes occur in the image on the screen?
9. Draw a simple ray diagram which shows why the magnification equals the ratio d_I/d_O for a real image.
10. Why is an "axial ray" of special importance in ray tracing?
11. Using a sketch, illustrate how the relative index of refraction between air and water can be measured.
12. In terms of ray behavior, explain why a "virtual" image is not "real".
13. An object point and its corresponding image point are called "conjugate". What is the meaning of this term?

14. Since window glass bends the light rays which pass through it, why does a window not act like a lens?
15. When white light is broken up into colors by a prism ("dispersion"), the red rays are bent more than the blue rays. Is the index of refraction for red light greater or less than for blue?

Solutions To Post-Tests

Test I

1. c) within the focal length.
2. 0.1 m.
3. 6.7 cm.
4. Real and inverted.
5. 100.
6. Smaller, to increase aperture.
7. 5 cm.
8. Creating a beam of parallel rays.
9. Positive versus negative image distance.
10. Arrow showing the direction of wave motion.
11. Lens surfaces are parallel near center.
12. Angle of reflection = angle of incidence.
13. $N_{12} = 1.72$.
14. Relative index between vacuum and medium.
15. $N_{12} = 0.75$.

Test II

1. f changes to keep d_I constant.
2. 40D.
3. Never (see answer to Question 6, Section A).
4. 6 in.
5. 1.5.
6. Away from the slide.
7. Hold object within focal length ($d_O < f$).
8. Image becomes dimmer. (Also sharper if hole is not too small; otherwise more blurry when diffraction limit approached.)
9. -
10. Direction after refraction by lens is known.
11. -
12. Rays do not actually originate from virtual image; however, ray directions are same as if image were a real source.
13. "Conjugate" means joined (i.e., by light rays).
14. Surfaces are parallel, so rays are bent back on leaving.
15. Greater.

IX LIST OF APPARATUS

The principle piece of apparatus for this module is a slide projector. The Kodak "Carousel" type is particularly convenient and is illustrated in the module. However, any slide projector is suitable as well as a conventional optics bench light source and lens. In addition to the projector, the following items are also required:

SECTION A

Tripod stand with clamps (2).
Cork with pin in it.
OPTIONAL:
Flat mirror.
Spherical mirror.
Hologram e.g., Edmund Scientific Co.
701 Edscorp Building
Barrington, New Jersey
08007
Colored filter

SECTION B

Narrow slit: can be made from an old slide frame and two double edged razor blades.(Slit width ~0.2 mm.)
Ray screen: can be made from a glass microscope slide and black masking tape. (Strips 5mm wide, 1mm apart.)
Transparent plastic container with at least one flat side.
Flat mirror (front surface preferable).
OPTIONAL:
Selection of lenses: concave and convex, any focal lengths.

INSTRUCTOR'S MANUAL FOR THE SOLENOID

CONTENTS

I INTRODUCTION

The Solenoid module provides an introduction to the study of magnetic fields, their production by electric currents, and the interaction between current-carrying wires and magnetic fields. The field of an iron bar permanent magnet and the field of currents flowing in a straight wire, a single loop, and a solenoid coil are studied.

The force between two permanent magnets, the force felt by a current-carrying conductor in a magnetic field, the torque felt by a current loop in a magnetic field, and the force between a permanent magnet and an idealized current-carrying solenoid are investigated. A model to predict the dependences of the force felt by the solenoid plunger on the current in the solenoid and on the position of the plunger in the solenoidal coil is developed.

II SPECIAL PREREQUISITES

In addition to the prerequisite of high school algebra which applies to the whole Physics of Technology series, the student should have had some previous exposure to the concepts of net force and net torque, and electrical current. These can either be introduced by previous study of other modules such as the Torque Wrench and the Multimeter, for example, or the instructor can provide the necessary background fill-in.

III TABLE OF CONTENTS OF THE MODULE

Prerequisites
Introduction
Goals
Section A
- Experiment A-1: Study of a Solenoid
- Magnetism
- Experiment A-2: Forces Between Magnets
- The Magnetic Field
- Experiment A-3: The Field of a Bar Magnet and Magnetic Induction
- Magnetic Field of a Current
- Experiment A-4: The Magnetic Field of a Current in a Straight Wire
- Field of a Straight Wire and the Right-Hand Rule
- Experiment A-5: Magnetic Field Produced by a Current Loop and by a Solenoidal Winding
- Summary

Section B
- Forces and Fields of Permanent Magnets
- Experiment B-1: Force Between Magnetic Poles
- Magnetic Field
- The Fields of Current-Carrying Wires
- Force on a Current-Carrying Wire in a Magnetic Field
- Summary

Section C
- The Torque on a Current Loop
- The Force Between a Coil and a Bar Magnet
- The Force on an Induced Pole in a Magnetic Field
- Experiment C-1: Force versus Plunger Position
- Experiment C-2: Force on a Solenoid Plunger as a Function of Current in the Winding
- Magnetic Flux
- Summary

IV LEARNING OBJECTIVES

The generalized goals are included in the module to help students who have not yet started the module to know what we hope they will learn from it. As the students gain more familiarity with the concepts and terms, and would like more detailed directions for their studying, you may want to share the following more detailed list of goals with them:

Section A:

Experiment A-1, Study of a Solenoid: Gain familiarity with the operation of the solenoid and how it can be used.

Magnetism: Define magnetic poles, ferromagnetism, magnetic repulsion and attraction, magnetic dipoles.

Experiment A-2, Forces Between Magnets: Identify the poles of an unmarked magnet, using a compass; observe the poles produced when a magnet is broken. Describe and discuss the phenomena observed.

The Magnetic Field: Define the magnetic field in terms of the force on a pole of a given strength. Define and use the field concept.

Experiment A-3, Field of a Bar Magnet and Magnetic Induction: Mapping of magnetic fields; observation of magnetization by induction. Sketch a magnetic field and describe the process of magnetic induction and its effects.

Experiment A-4, The Magnetic Field of a Current in a Straight Wire: Observe and map the magnetic field of a current in a straight wire. Describe and discuss the magnetic field observed for the straight wire, including its general appearance, and where it is stronger and weaker.

The Right-Hand Rule: Determine the direction of the magnetic field of a straight wire if given the direction of the current in the wire.

Experiment A-5, Magnetic Field Produced by a Current Loop and by a Solenoidal Winding: Sketch and describe the magnetic fields produced by a current loop and a solenoidal winding, including the effect of reversing the current. Observe and describe the increase in the field strength when an iron core is inserted into the solenoid. Observe and describe the force on a bar magnet inserted in the end of the solenoid. In particular, be able to predict an attraction or repulsion if the direction of the current in the solenoid and the polarity of the magnet are known.

Section B:

Forces and Fields of Permanent Magnets: Write the Coulomb force law for permanent magnets and make calculations with it, including calculation of forces, pole strengths, or distances when all of the other quantities are known. (Note from the discussion in section V of this guide that we have tried to leave to the discretion of the instructor the timing of discussions for the definition of the magnetic pole strength and the role played by the Coulomb law in its quantitative definition.)

Experiment B-1, Force Between Magnetic Poles: Measure the distance and the force between two permanent bar magnets and use a modified form of the Coulomb Law to calculate the strengths and approximate locations of the poles. Take measurements and calculate the induced pole strength in a soft iron bar, assuming that the location and strength of the permanent magnetic poles are unchanged, and that the location of the induced poles in the soft iron bar is the same as that of the magnet.

Magnetic Field: Calculate the magnitude of the magnetic field if given the force felt by a magnetic pole of known strength, and calculate the force that a given magnetic field will exert on a pole of known strength. Combine the Coulomb

Law and the definition of the magnetic field to calculate the magnetic field in the vicinity of a known distribution of magnetic poles.

The Fields of Current-Carrying Wires: Work with the expressions for the magnetic field near straight wires, single loops, and solenoidal coils, including calculation of the field value at specified points near known currents, or calculation of the current (or the location of the field point) when the magnetic field strength and the other quantity (or quantities) is known.

Force on a Current-Carrying Wire in a Magnetic Field: Work with the equation relating force, field, current, and length of wire, to calculate any one of the quantities when the others are known. Use it with other equations, for instance, equations giving the magnetic fields produced by given current configurations, to calculate the magnetic force acting on one current-carrying wire as a result of another.

Section C:

The Torque on a Current Loop: Define and discuss torque. Calculate torque when forces and lever arms are known. Discuss and describe how the magnetic forces on a rectangular current loop lead to a net torque with no net force on the loop. Use the expression for the torque on a loop to calculate torque, current, field, or dimensions of the loop when the other quantities are given.

The Torque on a Bar Magnet: Apply the concept of the force couple to the case of a bar magnet in a magnetic field and, when the other quantities are known, be able to calculate torque, pole strength, magnet size, or magnetic field strength for the case of a bar magnet placed in a uniform magnetic field.

The Force Between a Coil and a Bar Magnet: Compare the expression for the torque produced by a uniform magnetic field on a current-carrying loop and that which the same field would produce on a bar magnet. From this comparison, obtain an equation for the effective pole strength of the solenoid as a function of the current and the geometry of the solenoid. Using the Coulomb expression, write an expression for the force on the solenoidal plunger in terms of the current, the geometry of the solenoidal coil, the separation of the plunger from the solenoid, and the induced pole strength of the plunger.

The Force on an Induced Pole in a Magnetic Field; Experiment C-1, Force versus Plunger Position, and Experiment C-2, Force on a Solenoid Plunger as a Function of Current in the Winding: Discuss qualitatively some of the factors affecting the strength of the induced magnetic poles in the soft iron plunger, and hence, the force felt by the solenoid plunger. Plot a graph of the force on the plunger as a function of the insertion of the plunger at constant current, and a graph of the force on the plunger as a function of the current in the winding at constant insertion. Discuss the dependences shown by these graphs, including factors such as:

(1) The field of the solenoid depends linearly on the current through it;
(2) The field is approximately twice as great in the center of the solenoid as it is near an end;
(3) The strength of the induced pole depends directly on the field in which it finds itself, except for the fact that
(4) when the field is sufficiently large that the iron of the plunger becomes "saturated", the induced pole strength will no longer continue to increase.

Qualitatively discuss each of these factors and their effects on the

force of the solenoid, and also list other effects which may be present and may affect the force, such as shaping of the plunger, cladding of the solenoid, and the fact that the plunger may not, in real practice, be fully withdrawn from the solenoid. The students should be aware of the fact that many of the assumptions made in the development of the picture of the solenoid may be only approximate (for instance, the radius may not be very small compared to the length, the magnetic poles of the solenoid and the plunger are only approximately point poles, and in doing the experiment, the measurement of the insertion of the plunger is difficult to accomplish accurately).

Magnetic Flux: Define and calculate the magnetic flux through a given area, or calculate either the field or the area if the flux and the other quantity are known. Provide examples to show that the forces on current-carrying conductors in magnetic fields are such as to try to increase the magnetic flux through the plane of the conductors.

V DISCUSSION OF ACTIVITIES

The following is a description of the laboratory experiments, and suggested places in the module where the instructor may want to supplement the text with examples and more complete expositions.

Because of time constraints in laboratory scheduling, we have tried to write the laboratory experiments with as much flexibility as possible. For instance, many of the experiments can be done as "hands-on" demonstrations, or different groups may do different sections of an experiment. In the case of some of the field-mapping experiments, many alternatives involving very short to very long lab periods are possible. The instructor may want to have different groups do different magnetic field maps in the same lab period, to be followed by a short discussion of the results, or the instructor may want to have the students spend a relatively short time to sketch out each of the separate maps and then show the class more complete plots prepared earlier. The time estimates that are listed are intended only as a rough guide. In many cases, more than one experiment can be covered in the same class period.

Section A

In Experiment A-1 (estimated time, 10-20 min.), observe the action of a solenoid. You may want to use a demonstration format. Since many students may have experience with solenoids on cars or other equipment, draw upon such experiences to help the class predict what the solenoid will do when energized, and you may want to expand the discussion of the use of the solenoid, based on student input to the discussion. The format of the experiment has been structured to show that the force on the plunger depends upon the current, a point which will be examined more fully later in the module. The primary goal of this experiment is to provoke students to think about the solenoid.

In the section entitled "magnetism", there is a very brief reference made to ferrite and ceramic magnets. Since the iron bar magnet is probably more rarely seen nowadays than the inexpensive ferrite magnet, you may want to bring a bar magnet and a ferrite magnet to class for comparison. If the class is primarily urban, you may want to expand on the discussion of the compass as a direction-finding device and the definition of a north pole as the pole of the compass which points northward.

Experiment A-2 (estimated time, 20-30 min.) provides a qualitative identification of poles by means of a compass. If time permits, let some of the students examine a ferrite magnet with the aid of a compass to see that the pole configurations are usually much different than for a bar magnet. The discussion of stray magnetic fields due to structural building members and electrical currents has been left to the

instructor. You may want to demonstrate this by observing the compass at various locations in the room, either presenting a qualitative explanation or indicating that the rest of the module will explain how these factors can affect the compass. For economy, you may want to break only one or two magnets as a demonstration.

The abstract concept of magnetic field is difficult to convey. It may be helpful to discuss the distinction between the magnet which is considered to set up the field and the relatively weaker magnet that feels a force due to the field of the first, pointing out that it would be desirable to be able to use the field concept to describe the effect the magnet would have on any arbitrary magnet, placed at various points in the field. A discussion of how best to construct such a scheme would lead naturally into the concept of the field as "force per unit pole strength", making the field quantity independent of test pole strength. At this point in the module, we have used the pole strength as an arbitrary measure of the strength of a magnetic pole, since algebraic expressions are inappropriate in this section. A simple discussion that stronger poles will have larger values of $\underline{m}$, with possibly some examples (a typical bar magnet has a pole strength of 5-10 A·m), should help to clarify the basic concept, which is enough for the module to convey at this point.

Experiment A-3 (estimated time, 20-50 min.) begins as a traditional field-mapping experiment. The frequency of oscillation of the compass needle is used as a crude indicator of field strength (for small angular oscillations, the frequency goes as $\sqrt{\underline{B}}$). You may want to make reference to the discussion of the compass on pages 10 and 11. You might want to warn the students to keep the paper between the magnet and the iron filings, especially if you will have to do the cleaning up. The induced magnetization of the soft iron is qualitatively observed by means of the increase in the frequency of oscillation of the compass needle when the iron is magnetized. Since most soft iron will have some slight remanent magnetization, it may be difficult to observe the behavior of completely unmagnetized iron. One simple, effective, and inexpensive method of demagnetizing the nail is to pass the nail between the current electrodes of an operating soldering gun (using care not to get burned), removing the nail a few feet from the gun before turning it off. (Depending on the level of the class, this procedure can be used pedagogically either in this module or the "Transformer" module.) When this is done, the students can easily see that either end of the nail will attract either pole of the compass by magnetic induction and that repulsive forces are absent. Likewise, if the edge of the compass is brought near the center of the nail, either pole of the compass can be attracted to the nail. If the compass is held above or below the center of the nail, the compass will tend to align itself parallel to the nail, with no dependence on a reversal of the nail, head for point. They also should note from the speed of response of the compass that these forces are much smaller than for magnetic materials.

<u>CAUTION</u>: Carefully warn the students about the danger of even relatively low voltages when heavy current sources such as these are in use. Warn them not to touch any more than one part of the circuit at the same time in this experiment and in all the other electrical experiments.

Experiment A-4 (estimated time, 20-40 min.) begins the investigation of magnetic fields produced by electric currents. The apparatus is designed so that a wire can be threaded through the plotting boards, either puncturing a piece of paper placed on the board, or two pieces of paper can be slightly

notched and fitted together around the wire. The magnitudes of the fields produced in these experiments are small enough that it may be difficult in some cases to get good iron-filing patterns. It is not expected that the students will formulate the right-hand rule for themselves, but the effort to devise any form of rule should increase student understanding of the properties that such a rule must have. Good students may be able to devise their own rule, but most will probably find pages 14 and 15 necessary.

Repeat the warning of the danger from electrical shock before starting Experiment A-5 (estimated time, 60-90 min.). This experiment investigates the geometry of the magnetic field for a single loop and a solenoidal current-carrying conductor. You may want to leave the solenoidal windings permanently threaded on some boards and let the students exchange boards. The solenoids can be wound fairly uniformly if a wooden or plastic foam cylinder of the appropriate size is cut in half lengthwise and then sandwiched above and below the board while the coil is wound loosely enough so that the half-cylinders can be slipped out. Because it is too time consuming to wind a great number of turns on the boards, the force felt by the bar magnet will probably be quite small. It should, however, be measurable. It should be observable that the force reverses when the current is reversed, and that the presence of the iron core increases the force. The discussion of Experiment A-5 requires the use of the superposition concept for magnetic fields to explain the increase in the field for the case of multiple loops. You may want to initiate a discussion of the addition of magnetic fields, including such questions as whether the fields of permanent magnets can be superposed on current-produced fields, and what procedures must be followed to take the directions into account if the field contributions at a point are not parallel. If your students are familiar with vectors, the discussion can be quite complete, but if they are not, you may want to consider a qualitative diagrammatic discussion.

Section B

Coulomb's Law is introduced, using the algebraic expression. As the first use of algebra in the module, Coulomb's Law may require added class time for discussion. For instance, you may want to use the equation to explain why distant poles have weaker effects than closer poles. The students will probably have fewer problems with the force-distance relationship than with the concept of magnetic pole strength. Up to this point, the module has used m as a measure of the strength of the magnet, but the method by which the measurement can be made has not been stated. In the spirit of going to the experiment as early as possible to see what the physics means in actual practice, the verbal argument that Coulomb's Law can be used not only to describe the force law between magnets, but also to quantify and measure the magnetic pole strength, has been left to the discretion of the instructor. If the class can grasp the concept, you may very well want to initiate further discussion at this point. Alternatively, you can begin the experiment, leaving the concept of pole strength as an unspecified measure of the magnet's strength. In this case, in steps 5 and 9 of Experiment B-1, it should be pointed out that Coulomb's Law has been used for the measurement of the pole strength, and a more complete discussion should then be provoked. The students will probably be mystified by the units of pole strength, A·m, and should be reassured that they will make more sense in Section C. The introduction to Section B has also left it to the instructor to decide whether or not at this point to provide further discussion of the interaction of real dipolar magnets. You will probably not want to write out all four of the Coulomb terms for the force between two dipoles, unless the class is exceptional. However, you may want to draw a diagram

showing the other forces which must be considered in Figure 21 when the approximation that only the closest poles interact significantly is not valid.

Experiment B-1 (estimated time, 45-70 min.) is designed to use Coulomb's Law to measure the pole strengths of two identical bar magnets and to locate the effective positions of the magnetic poles. The experiment may also be done vertically by hanging one magnet from a spring scale, sandwiching the shims between the magnets, and then reading the scale as the lower magnet is slowly pulled downward with a steady force. The scale reading must, of course, be corrected for the weight of the top magnet in order to determine the force needed to separate the magnets. The induced pole strength of an unmagnetized iron bar is measured using the assumptions that the pole strength of the magnet is unchanged, and that the position of the induced pole in the iron bar is the same as that of the pole in the magnet.

In the section entitled "Magnetic Field", you may want to treat the superposition of fields more fully. In particular, the poles in problem 3 lie along a line, so that the vector nature of the superposition process is not obvious. If your class has experience with vectors, you may want to use examples requiring vector addition. Likewise, in the treatment of the fields of current-carrying wires, you may also want to discuss how, in the plane of the loop, in its interior, the magnetic fields from all of the segments of the current loop are directed parallel to each other and therefore superpose to produce a larger field than would be produced in the vicinity of a single wire. This discussion can then easily be extended to the superposition of the fields of the separate loops when they are combined to form a solenoid.

The force on a current-carrying wire in a magnetic field was not treated experimentally because it is a difficult measurement to make without high currents and high fields or both, so that inclusion of such an experiment would have increased the apparatus cost for the module. If equipment for such an experiment is available, you may want to include it as either a student experiment or a demonstration. A high-current DC power supply (10-15 A) is enough, however, to construct a fairly simple and effective demonstration to show the existence of the force on a current-carrying wire due to a permanent magnet and also that due to the field of another current-carrying wire. Hang a length of enameled copper wire between two supports that are 1.5 to 3 meters apart, letting the wire hang loosely with about .5 m sag. When a large current is passed through the wire, it will react visibly to the bar magnets used in this module. The effects of reversal of current direction and the magnetic field can be observed. If two such wires are hung a few centimeters apart, they can be observed to move slightly when high currents are passed through both. Reversal of the current in one of the wires reverses the force on each wire. To see this effect requires a fairly high current, and even so, the motion of the wires is fairly slight, but it does provide an effective demonstration. When doing these demonstrations, the wires may smoke and you may blow some fuses. Our students have enjoyed these extra "special effects".

Again, if your class has had more experience with vectors, you may want to provide a more complete discussion of the magnetic force on a current-carrying wire in its vector product form.

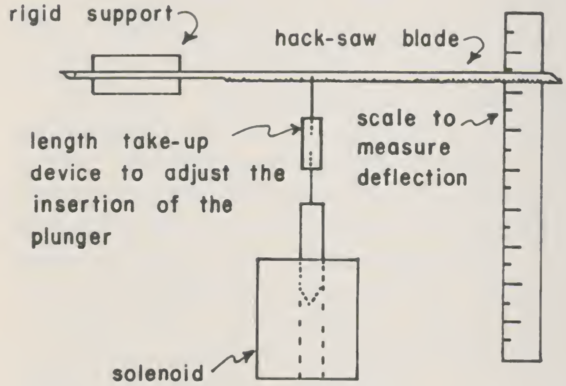
<u>Section C</u>

In Section C, the physical principles that have been treated earlier in the module are used to construct a physical model to predict the behavior of a real solenoid. Fewer new physical principles are presented in this section, but it better illustrates how the physicist goes about the applica-

tion of the physical principles to a real device. The student will find this section more analytical than the earlier sections.

The first part of Section C develops the analysis of the torque felt by a single current-carrying loop in a uniform magnetic field, using the concept of the force couple. (If your class is particularly interested in the application of the physics to real devices, you may extend this discussion to consider D'Arsonval meter movements and electric motors, including the use of a commutator to reverse the current flow for the case of the d.c. motor.) The torque which a bar magnet would feel when placed in the same magnetic field is analyzed. (Here, it could be pointed out that this analysis applies to the compass that was used earlier in the module to map the fields.) The fact that the current loop and the bar magnet behave identically in an external magnetic field if (iA) for the loop equals (mL) for the magnet is then used to calculate the magnetic pole strength of the solenoid in terms of its dimensions and the current through it. (It can be pointed out here that the units for the pole strength of the solenoid are in fact expressed in A·m.) The Coulomb Law is then used to calculate the force between the solenoid and a permanent magnet.

Experiment C-1 (estimated time, 45-80 min.) is designed to measure the force on the plunger as a function of its position in the field of a solenoidal coil. Because of the fact that the throw of most solenoids is only a few centimeters, one of the biggest inaccuracies in this experiment is the measurement of the insertion. The apparatus provided by Thornton Associates will not be exactly as shown in the module, but the operation is fundamentally the same, at a considerable reduction in cost. At the time of printing of this manual, the apparatus is projected to be similar to the diagram shown below. In operation, the point of attachment to the hacksaw blade should lie on the axis of the solenoid.

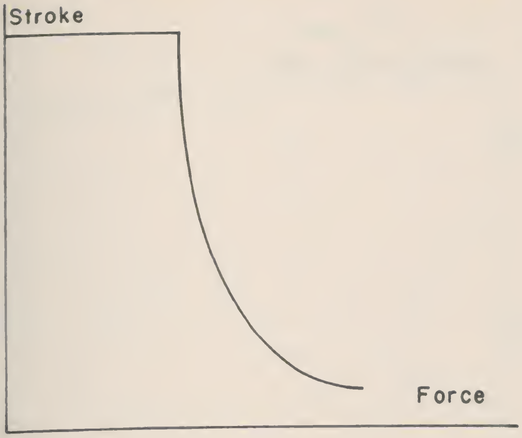


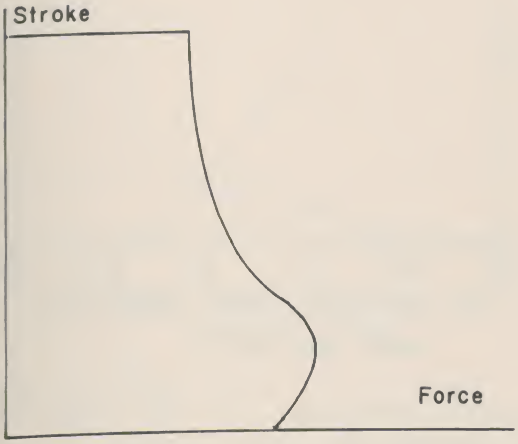
Replacement for Figure 41.

The electrical apparatus will perform the same functions as the equipment shown in the module, but will also look different. The hacksaw blade will provide a convenient reading which can be calibrated in newtons if desired by attaching a string to the take-up device, running it through the center of the solenoid, with the plunger removed, over a pulley to a weight hanger.

Because the characteristics of the solenoid depend on the cladding configuration, the curves obtained may not look exactly like Figure 42. In addition, because 0% insertion is not possible, the plotted curves will represent only a part of the right-hand side of Figure 42. A plot for the solenoid #11-C-24V made by Guardian Electric Co. is shown in Sect. VI. Other solenoids may have different characteristic plots. If Thornton Associates supplies a different solenoid, its plot will be supplied. The dependence of these plots on the solenoid configuration is illustrated by the other plots shown here.

A calibration plot of force vs. deflection for the prototype apparatus is also shown below in Section VI.





Experiment C-2 (estimated time, 45-80 min.) is intended to show how the force on the plunger varies with current in the solenoid. The apparatus is the same as for Experiment C-1, and the above comments apply. In order to keep the length of the module reasonable, ferromagnetism is treated only superficially. You may want to augment this material, or you may want to follow the Solenoid with a module such as the Transformer, which treats ferromagnetic behavior more fully.

The discussion of magnetic flux is included for completeness of the treatment of magnetic fields, and is essential if the Solenoid is being used as a prerequisite for the Transformer.

VI SAMPLE DATA AND QUESTION ANSWERS

Exp. A-1, Examination of a Solenoid:
When the solenoid is energized by a current flow the plunger is pulled into the solenoid. It is always pulled into the solenoid; no force without power; force increases as current increases.

Exp. A-3, Field of a Bar Magnet:
Step 6 The filings line up parallel to the magnetic field just as the compass needle did. The resulting patterns are very similar.

The Effects of Magnets on Non-Magnetized Iron:
Step 1 Both ends of the compass needle will be attracted to the piece of iron with about the same force. When the compass is placed over the center, the compass needle will align itself along the iron. See Section V for method to demagnetize iron.
Step 2 When a magnet is near the far end of the iron, the compass needle, when jiggled, will vibrate more rapidly than otherwise. As the magnet is withdrawn, the frequency of the compass needle decreases, indicating that the strength of the field is reduced.
Step 3 When the magnet is reversed, the compass needle also reverses itself, indicating that the magnetic field at the compass end of the iron has reversed.

Exp. A-5,C Field of Loop and Solenoid:
The iron core will increase the strength of the magnetic field as indicated by the compass needle, which vibrates more rapidly.
Part D
Sample data: 22-turn, 10-cm-long solenoid
magnet weight: 1.2 N
current on: 1.3 N at 10 A
reversed current: 1.1 N at 10 A
Force is increased by about .2 N with an iron core.

Exp. B-1, Forces Between Magnetic Poles:
Steps 1-4 shim thickness - .22 mm.
for 1 shim, force = ave. of 2.60, 2.70, 2.70 N = 2.66 N
for 3 shims, force = ave. of 2.0, 2.0,

2.0, = 2.0 N

Step 5 $\underline{F}_3$ = 2.66 N $\underline{F}_4$ = 2.00 nt
$\underline{d}_3$ = .22 mm $\underline{d}_4$ = .66 mm
$\underline{d}_o$ = 1.3 mm
$\underline{m}_1 = \underline{m}_2$ = 14.5 A·m

Step 6 for 6 shims, $\underline{f}$ = ave. of 1.3, 1.4, 1.5 N = 1.4 N, measured. $\underline{f}$ calculated = 1.4

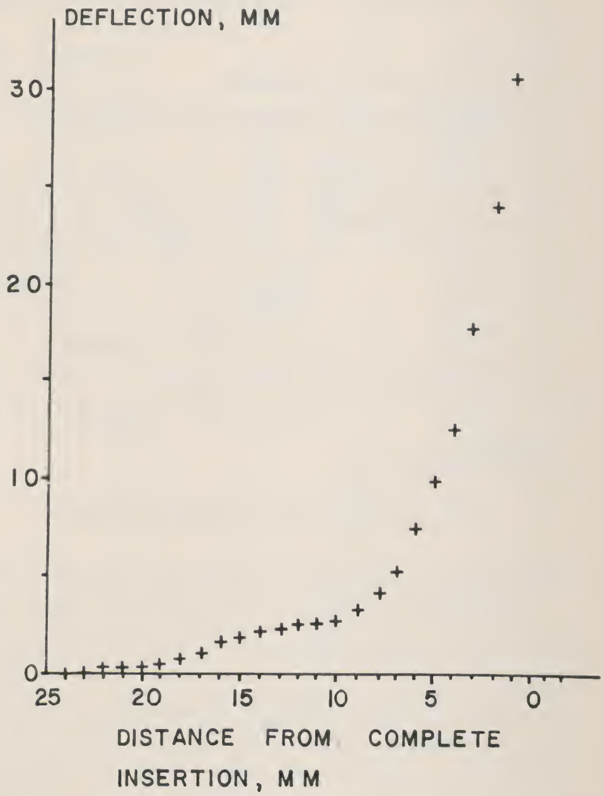
Steps 8-11 for 1 shim, $\underline{f}$ = ave. of 2.0, 2.0, 2.1 N = 2.03 N
for 3 shims, $\underline{f}$ = ave. of 1.3, 1.4, 1.4 N = 1.36 N
calculated induced pole strength for 1 shim: 11.1 A·m
calculated induced pole strength for 3 shims: 10.0 A·m

Exp. C-1, Force vs. Plunger Position:
Note that the apparatus to be supplied by Thornton Associates will not be the same as that pictured in the student module. It is discussed in Sec. V above. Detailed instructions will be supplied with the apparatus. Data provided here was taken from a prototype model using a standard hacksaw blade.

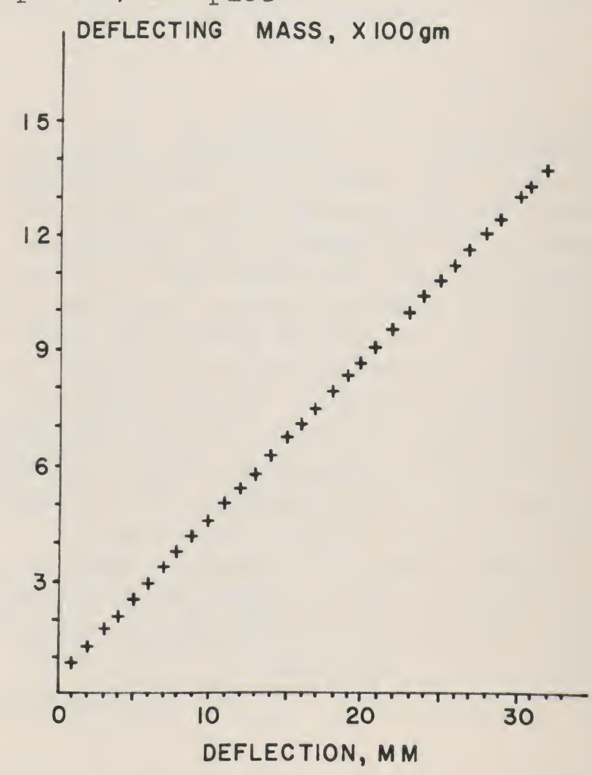
The first figure is a plot of deflection vs. distance from complete insertion. It was taken with a solenoid current of 300 mA, using a #11-C-24VDC solenoid manufactured by the Guardian Electric Co. The other plot is a calibration curve of the hacksaw blade which was made by removing the solenoid plunger, and passing a cord through the solenoid and over a pulley. The deflection (force) vs. distance plot should be recognizable as the right-hand portion of Figure 42.

Exp. C-2, Force vs. Solenoid Current:
The comments above and in Section V with regard to the apparatus also apply to Experiment C-2. The plot given here shows the deflection of the hacksaw blade vs. the solenoid current. The deflection can be converted to force by means of the calibration curve for the hacksaw blade given above for Exp. C-1.

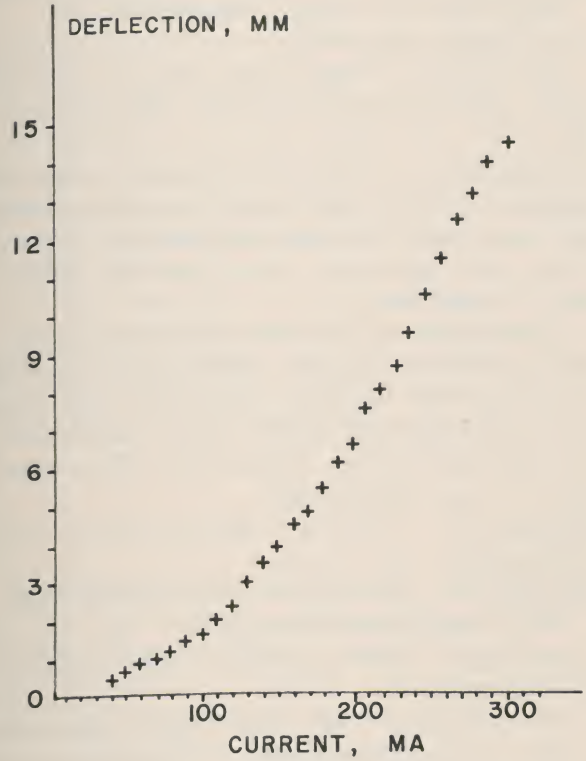
Exp. C-1, 1st plot



Exp. C-1, 2nd plot



Exp. C-2 plot



Questions, Exp. C-2

1. The scale reading present with no current flowing must be subtracted from the final reading to give the force actually caused by the current.
2. The mechanical leverage is not important. Correcting for this would change the scale size on one axis of your graph, but would not change the shape of the graph.
3. You should see this in the experiment.

VII SOLUTIONS TO PROBLEMS AND QUESTION ANSWERS

Exp. A-1

Question 1: Geographic north is roughly indicated by the north-seeking compass pole. However, because the magnetic pole is not at the same point on the earth as the geographic pole, a better direction for north is found by sighting on the North Star. The position of the sun is also a good guide when correlated with the time of day.

Question 2: The magnetic pole near the north geographic pole must be a "south" magnetic pole.

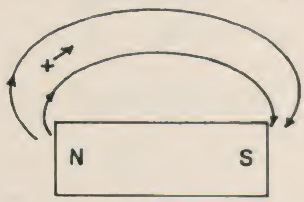
Exp. A-3

Question 1: The length of the magnetic field arrow is proportional to the force that would be felt on the north pole of a long magnet placed at the tail of the arrow. The direction of the arrow is in the same direction as the force.

Question 2: Each small iron filing becomes a small magnet itself when placed in a magnetic field. These small north poles then feel forces in the same direction as a compass needle would. Furthermore, the south pole of a filing is attracted to the north poles of nearby filings; the filings then "chain up" in lines along the magnetic field.

Question 3: The strongest regions of the magnetic field are near the poles of the magnet. The field becomes weaker as the distance from the magnet is increased.

Question 4: Both the compass plots and the iron filings show that the field lines follow a regular pattern, and in any small area are nearly parallel. Between any two field lines, the direction must be "between" that of the outside lines. (The instructor may want to discuss the fact that magnetic field lines cannot cross.)



Question 5: One reason for the deflection might be that the compass needle, actually a magnet, induces a small magnetic pole in the iron, which then attracts it. Another possible reason is that when the iron is brought near the compass, it disturbs the earth's magnetic field in its vicinity.

Question 6: When a permanent magnet comes near a piece of iron, the iron

becomes a magnet by induction. This new magnet then induces another piece of iron to become a magnet. These induced magnets attract each other north pole to south pole (or see page 11).

Exp. A-4

Question 1: See Figure 16.

Question 2: No, the magnetic field lines begin and end only on themselves.

Question 3: See Right-Hand Rule, Figure 17.

Question 4: The magnetic field created by a current will be used to attract an iron plunger.

Exp. A-5

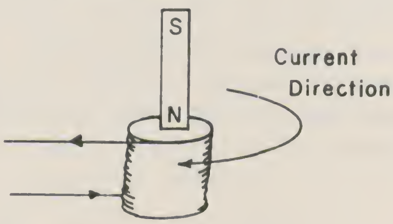
Question 1: The student should be able to apply the Right-Hand Rule and show that it agrees with observations.

Question 2: The shape of the field of the solenoid is very similar to that of a bar magnet. Reversing the current changes the field in the same manner that flipping a bar magnet would.

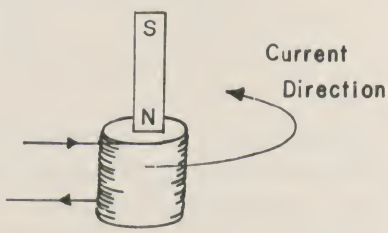
Question 3: The strength of the solenoid's field increases with the number of turns for the same current.

Question 4: The iron core increases the strength of the field.

Question 5: For attraction



For repulsion



The nearest pole of the electromagnet attracts or repels the closest pole of the bar magnet.

Exp. B-1

Question 1: Force greater for a small shim thickness.

Question 2: The graph is a curve because force drops as $1/\underline{r}^2$, where $\underline{r} = \underline{d}_o + \underline{d}$.

Question 3: Yes; the farther the bar magnet is from the iron bar, the lesser the strength of the induced pole, because the magnetic field at the iron bar is smaller.

Question 4: As accurately as most spring scales may be read, the Coulomb force law is obeyed. However, if more accurate devices were used, the poles on opposite ends, ignored so far, would have to be considered.

Problem 1: .08 A·m = $\underline{m}'$

Problem 2: $\underline{r}$ = .2 m

Problem 3: $\underline{B} = 1.8 \times 10^{-6}$ T directed away from the north pole

Problem 4: $\underline{F}$ on S pole = 3.2×10^{-4} N (attractive)
For N pole = 3.6×10^{-7} N (repulsion)
$\underline{F}_{Npole}$ is completely negligible compared to the attractive force above.
Hence, $\underline{F} = 3.2 \times 10^{-4}$ N attractive.

Problem 5: $\underline{B} = 1.25 \times 10^{-5}$ T

Problem 6: $\underline{B} = 3.93 \times 10^{-5}$ T, greater than $\underline{B}$ in problem 5 by a factor of π.

Problem 7: Current is assumed to remain at 5A. $\underline{B} = 6.3 \times 10^{-3}$ T, about 160 times greater than the field in #6.

Problem 8: Assume the wires are each 1 m long. $\underline{i}'$ = .625 A, same direction as the other current.

Problem 9: $\underline{r}$ = 4.5 m; the currents are in opposite directions.

Problem 10: $\underline{F} = 6 \times 10^{-4}$ N

Problem 11: $\underline{B} = 2 \times 10^{-5}$ T

Problem 12: 4 A = $\underline{i}$

Problem 13: 4 = no. of turns

Problem 14: 1/2 the original torque

Problem 15: $\underline{F}$ = .283 N
$\underline{T} = (\underline{mB})\ \underline{L} \sin\alpha = \text{Force}\ \underline{L} \sin\alpha$

Problem 16: .5T = $\underline{B}$, yes

Problem 17: $\Phi = 6.28 \times 10^{-2}$ Wb

Problem 18: Φ = .35 Wb

Problem 19: Using the Right-Hand Rule on any segment of wire indicates that each piece of wire feels an outward force. Since the current in each piece of wire must be the same, and the field is uniform, the end result is that the flexible wire is circular. This geometric shape, the circle, maximizes the amount of flux through it for a given length of wire.

If the current is reversed, the loop will collapse in on itself and then spread out again. A piece of wire on the right side will "flip" onto the left side, again forming a circle.

VIII POST-TESTS

The instructor may prefer to select his or her own mix of questions from those suggested here, rather than to use these tests intact. You may or may not want to provide the students with the algebraic relations. In all questions, the magnetic field of the earth should be neglected unless otherwise specified.

Test 1

Section A

1. Describe briefly why a compass lines up parallel to the magnetic field in which it is placed. Use a diagram. What property of the earth are we using when we find our way in the woods with a compass? Why must we be careful not to take a compass reading when it is near a gun, a knife, or other iron or steel articles?
2. (a) If one end of a bar of iron attracts the north pole and repels the south pole of a compass, and the other end attracts the south pole and repels the north, what can you conclude about the bar? Why?
(b) If the end of a bar of iron sometimes attracts the south pole of a compass, and sometimes the north pole, and the other end of the bar behaves similarly, what can you conclude about the bar? Why?
3. Sketch the magnetic field set up by a current flowing in a straight wire. State the right-hand rule or some other rule that will give the direction of the field if the current direction is known.
4. Sometimes kids wrap many turns of a wire around a nail, connect the wire to a battery and observe that the wire-wrapped nail has become an electromagnet. Discuss why this happens, using your experiences with this module.

Section B

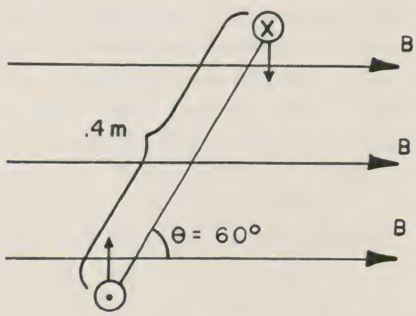
5. In doing the experiment where you measured the force between two magnetic poles:
(a) How would the force change if you replaced one of the magnets with a magnet whose poles were twice as strong?
(b) How would the force change if you replaced both of the magnets with magnets having pole strength equal to one third of that of the original magnets?
(c) How would the force change if the shim thickness is changed so that the magnetic poles have a separation four times that of the original separation?
(d) How would the force change if both (a) and (c) were done?
6. If the magnetic field .25 meters from a wire is observed to be 4×10^{-6} T, and if there are no other sources of magnetic field in the vicinity, what current is flowing in the wire? Sketch the direction of the field. (Near a current-carrying straight wire, $\underline{B} = 2\underline{k}\frac{i}{r}$).
7. If you were an engineer designing a machine, and the air-core solenoidal coil which you had available did not produce a strong enough field, what suggestions could you make to the manufacturers of the coil so that they could redesign the coil to produce a stronger field? (Recall

that for an air-core solenoid $B = 4\pi k \frac{Ni}{L}$, and also recall the effect of an iron core in an earlier experiment in this module.)

8. If the magnetic field produced at a distance r from a wire carrying a current i is $B = \frac{2ki}{r}$, and if the force on a wire carrying a current i_2 in a magnetic field B is $F = Bi_2L$, show how we can find the force between two parallel wires, each of length L, a distance r apart, when one has a current i and the other a current i_2.

Section C

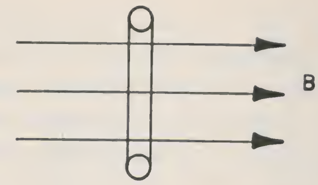
9. What torque will be exerted on a current loop .2 by .4 m, carrying a current 5A in a uniform magnetic field $B = 0.2$ T as shown in the diagram?



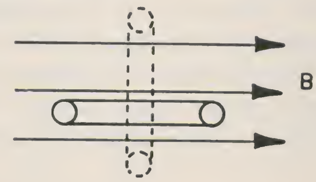
10. If a 1000-turn circular solenoid of radius .01 m and length .08 m, carries a current of 3 amperes, what will be its effective pole strength m? (Recall for a solenoid, $m = \frac{NiA}{L}$.)

11. Discuss how the force on a solenoid plunger, kept at constant insertion, should depend on the current in the solenoid as the current is increased. Give reasons for the behavior.

12. A wire loop .5 m by 1.6 m is placed in a magnetic field of .2 T such that the field is perpendicular to the loop.
 (a) What is the magnetic flux through it?



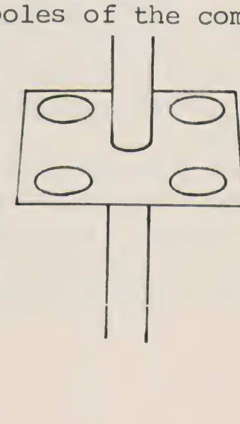
 (b) If the loop is turned 90°, what is the flux through it? What has been the change in the flux?



Test 2

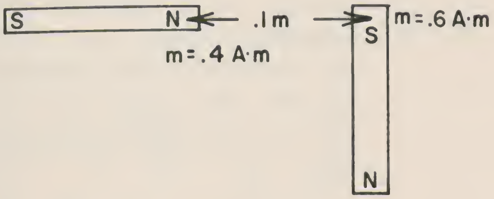
Section A

1. Describe what happened when the special magnet was broken. Sketch its magnetic field before you broke it, and the magnetic fields of the two pieces. If you kept breaking the pieces smaller and smaller, could you separate a north from a south pole?
2. Describe how you can use a compass to determine whether a bar of iron is magnetized or unmagnetized. Discuss why your method works.
3. Describe why the iron filings gave you a "picture" of a magnetic field. You may want to think of them as little compasses once they have been magnetized by the field of the magnet.
4. Complete the sketch to show how several compasses placed near a straight current-carrying wire will point. Show the direction of the current flow and label the poles of the compasses.



Section B

5. What force will a north magnetic pole of strength .4 A·m feel when placed at a distance of .1m from a south pole of strength .6 A·m, as in the diagram? Remember that your answer is not complete unless you also include the direction of the force. Assume that the magnets are long enough so that the forces due to the poles that are farther apart are much smaller than those between the closest poles. Use arrows to indicate the forces that the closest poles would feel if you could not neglect the forces due to the farther poles.



6. Find an algebraic expression for the force that will be felt by a magnetic pole of strength $\underline{m}$ A·m placed at a distance $\underline{r}$ m from a wire carrying a current $\underline{i}$ amperes. (Recall that for a straight wire, $\underline{B} = 2\frac{ki}{r}$.)
7. What current must flow in a circular wire loop of radius .2m if the magnetic field at the center is to be 6.28×10^{-5} T?
8. A power transmission line carrying a current of 100 A is perpendicular to the direction of the earth's magnetic field, $\underline{B}_e = 6 \times 10^{-5}$ T. What is the total force on 1 km of this line? The current carried on such lines is usually alternating, i.e., the current reverses and flows in the opposite direction every 1/120 sec. What effect will this have on the force exerted on the line?

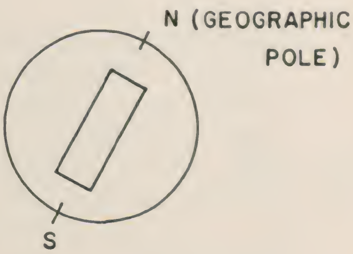
Section C

9. Show that the torque on a magnet placed in a uniform magnetic field will align the magnet parallel to the field. How did we use this effect in plotting the magnetic fields earlier in the module?
10. If you wanted to increase the pole strength of a solenoidal winding (neglect the effects of iron cladding), would it help to increase the number of turns by adding windings with the same pitch onto the end of the solenoid (thereby making it longer)? Justify your answer algebraically.
11. How would you expect the force on the plunger of a solenoid to vary with current in the solenoid if the plunger was a strong permanent magnet so that the current in the solenoid did not appreciably affect its pole strength? Why?
12. Give an example of a possible experiment to show that a current loop will feel a force that tries to increase the magnetic flux through it. Prove that the current loop in your example will feel such a force.

Test 3

Section A

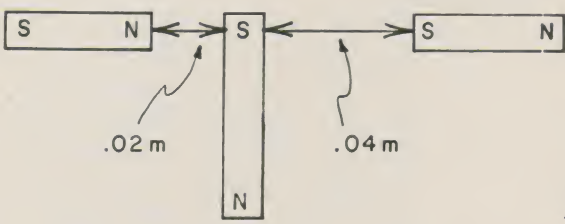
1. The diagram shows the earth and the imaginary bar magnet that can be thought of as equivalent to the source of its magnetic field. Sketch on the diagram a rough picture of how you think the earth's field would look. What is the polarity of the pole nearest the earth's geographic north pole?



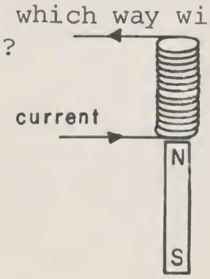
2. What information does the magnetic field of a magnet or a current give us? Define the magnetic field strength $\underline{B}$.
3. Suppose that you drop a small iron screw down a deep hole which is so small that your hand won't fit. If you have a strong magnet which is also too large to fit in the hole and a long iron screw driver that will reach to the bottom, describe a way by which you can get the screw out of the hole. Discuss why your method would work.
4. Sketch the magnetic field of a single current loop, and that of a solenoid with several turns. How do these fields compare? How do they differ? Why is the field of the solenoid stronger than that of the single loop?

Section B

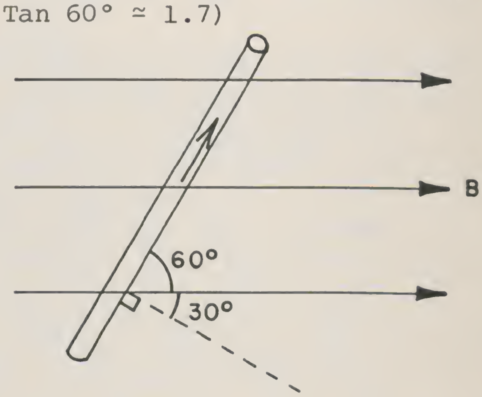
5. Consider the magnets shown in the diagram. If all of the poles have pole strength $\underline{m}$ = .3 A·m, and if the 3 magnets are long enough so that the forces due to the farther ends of the magnets are very small, what is the net force on the south pole of the middle magnet? In what direction?



6. A magnetic north pole of strength $\underline{m}$ = .5 A·m feels a force of 2.5 x 10^{-3}N, due to a magnetic field. What is the strength of the field? What force would be exerted on a south pole of the same strength? How would the two forces differ?
7. A long magnet of pole strength $\underline{m}$ = 2.0 A·m and weight .150 N is held right at the end of a long air-core solenoid. Both the solenoid and the magnet are long enough so that the far pole of the magnet can be neglected. If the solenoid has 300 coils, and is .03 m long, what current will it have to carry so that the solenoid will support the magnet? If the magnet is then released, which way will it move, and why?



8. A 3-A current is flowing through a wire .5 m long in a uniform magnetic field $\underline{B}$ = 4 x 10^{-5} T as shown in the diagram. Calculate the magnitude of the force that the wire will feel. (Cos 60° = sin 30° = .5, Cos 30° = sin 60° ≃ .9, Tan 30° ≃ .6, Tan 60° ≃ 1.7)



Section C

9. What is the maximum torque that a double current loop of width 4 cm, length 5 cm, and carrying 1 ampere will feel when placed in a magnetic field $\underline{B}$ = 3 x 10^{-4} T? What factors can be varied in order to construct a similar device that will feel a torque a hundred times greater? Which one of these factors would you use to cause most of the needed torque increase?
10. If the effective pole strength

of a solenoidal winding is given by $\underline{m} = \frac{Nia}{L}$, what force will be felt by a magnetized iron plunger having a pole strength $\underline{m}'$ and located a distance $\underline{r}$ from the pole of the solenoid? Show your work.

11. How would you expect your plot of $\underline{F}$ vs. $\underline{i}$ for constant insertion of the plunger to behave if the iron of the plunger did not saturate? Why?

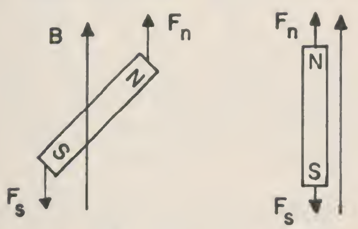
12. A wire loop is placed in a magnetic field of 6×10^{-5} T so that the magnetic flux through it is a maximum. If one dimension is .3 m, what must be its other dimension if the total flux is to be 18×10^{-6} Wb? What must be the relative orientation of the loop and field for the maximum flux?

Answers to Post-Tests

Test 1

Section A

1. The north pole feels a force in the direction of the magnetic field, but the south pole feels a force in the opposite direction. The end result is that the compass needle pivots until it is aligned with the field.



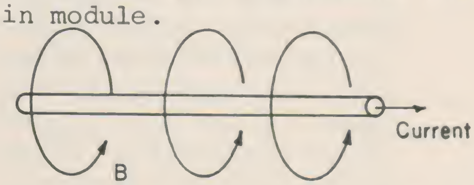
The earth has a magnetic "south" pole near the geographic north pole.

Any iron or steel will disturb the earth's magnetic field in its vicinity and consequently cause errors in any compass reading.

2. (a) Only a north pole can attract a south and repel a north, and by the same argument, the other end must be a south pole-i.e., a magnet.

(b) Bar must be unmagnetized iron. Neither pole of compass is repelled; therefore, attraction must be due to induction of pole in unmagnetized bar.

3. Any rule that will predict direction, e.g., right-hand rule in module.



4. The wire wrapped around the nail forms a solenoid with the soft-iron nail as the core. A DC current in the wire sets up the magnetic field which is strengthened by the nail.

Section B

5. (a) twice as great
(b) 1/9 as large
(c) 1/16 as large
(d) 1/8 as large

6. 5 A = $\underline{i}$

7. Add an iron core, design for higher current, increase the number of turns per length.

8. $F = Bi_2L = \frac{2ki_1}{r} i_2 L$

Section C

9. .04 Nm

10. $\underline{m}$ = 11.8 A·m

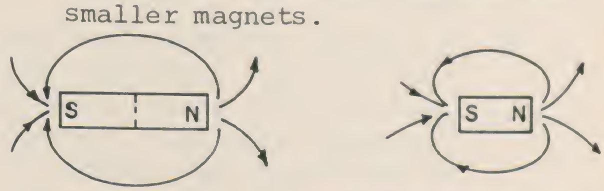
11. For low currents the force should increase as i^2, or $F = Ki^2$. As the iron becomes saturated magnetically, so that its induced magnetic pole cannot increase further, then the force increases as $\underline{i}$, or $F = K'i$ for large currents.

12. (a) .16 Wb
(b) 0.0 Wb; -.16 Wb

Test 2

Section A

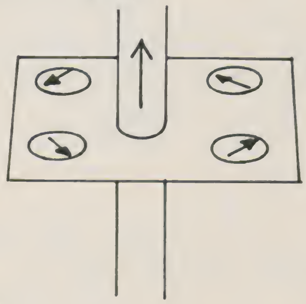
1. The one large magnet became two smaller magnets.



BEFORE EACH PIECE AFTER

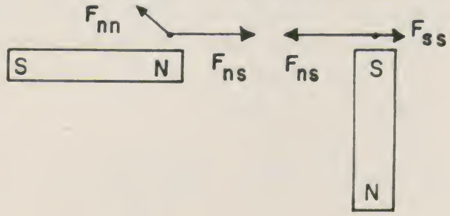
No matter how small the pieces become, you will never separate the north from the south poles.

2. If the bar is unmagnetized, either compass pole, north or south, should be attracted to either end of the iron bar. When either end of the compass needle approaches unmagnetized iron, an opposite pole is induced in the iron, resulting in an attraction. If one end of the compass needle is attracted to one end, and the other end of the compass needle repelled, then the iron is a magnet.
3. By induction, the iron filings become small magnets very similar to a compass needle. As you tap the paper they align themselves with the field and "head to tail" to result in an approximate picture of the magnetic field.
4.



Section B

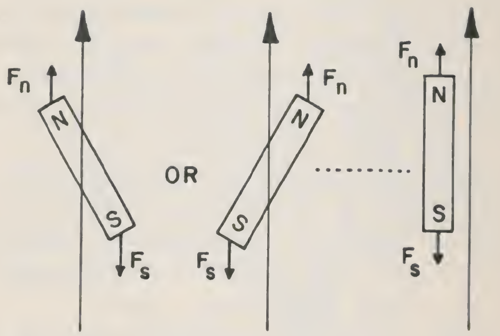
5. 2.4×10^{-6} N attractive



6. $\underline{F} = 2\frac{k\underline{i}}{\underline{r}}\,\underline{m}$
7. 20 A = $\underline{i}$
8. 6 newtons perpendicular to $\underline{B}$ and the wire; since the current reverses every 1/120 sec, the force will also reverse. If the force were larger, it would tend to make the wire vibrate.

Section C

9.



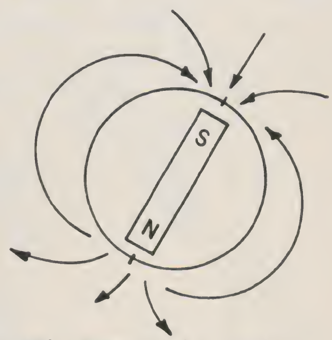
We used the compass needle, a small pivoted magnet, to find the direction of the field.

10. Since $\underline{B} = \frac{4\pi k N i}{L}$ for a long solenoid, if we increase $\underline{N}$ without changing the pitch, we increase $\underline{L}$ by the same proportion. Hence, $\frac{N_i}{L_i} = \frac{N_{final}}{L_{final}}$ and $B_i = B_{final}$.
11. $\underline{B}$ field of the solenoid is proportional to $\underline{i}$, and since $\underline{F} = \underline{B}m_{permanent\ magnet}$, the force would increase proportional to $\underline{i}$, for a constant insertion.
12. See pages 42 and 43.

Test 3

Section A

1.

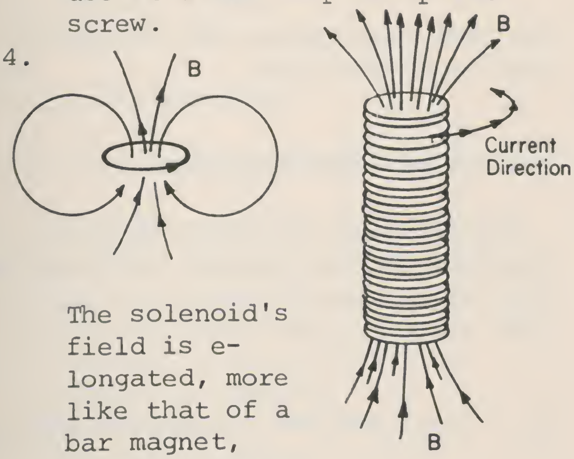


a south magnetic pole

2. See pages 7 and 24.
3. Place the screwdriver in the hole touching the screw. Approach the screwdriver with the strong magnet. Two poles will be induced in the screwdriver, one on each end. The induced pole near the screw will induce magnetic poles in the screw, which cause the screw to be attracted by the screwdriver. Another possibility would be to

magnetize the screwdriver and use it alone to pick up the screw.

4.



The solenoid's field is elongated, more like that of a bar magnet, and is stronger in the center for equal currents. The solenoid's field is larger because the magnetic fields due to each individual loop add vectorially inside the solenoid.

Section B

5. $\underline{F} = 2.8 \times 10^{-5}$ N, toward the left.
6. 5×10^{-3} T = $\underline{B}$; magnitude of the force on a south pole would be the same, but direction opposite.
7. 12 A = $\underline{i}$; magnet will move upward into solenoid because field is stronger inside.
8. $\underline{F} = 5.4 \times 10^{-5}$ N into the paper.

Section C

9. $\underline{F} = 1.2 \times 10^{-6}$ Nm
   The factors of current, area, and number of turns may be varied. Most of increase could be obtained by increased number of turns.
10. $\underline{F} = k \frac{mm'}{r^2}$ and $\underline{m} = \frac{Nia}{L}$

    then $\underline{F} = \underline{k}[\frac{Nia}{L}]\frac{m'}{r^2}$
11. If the iron did not saturate, the force would continue to increase as $\underline{i}^2$, because the induced pole in the plunger is proportional to $\underline{B}$, which is proportional to $\underline{i}$.
12. $\underline{x}$ = 1m; field perpendicular to plane of loop.

IX LIST OF APPARATUS

1. Solenoid such as Guardian Electric Co. #11-C-24 VDC with force-measuring apparatus available from Thornton Associates, or the equivalent described in Section V above.
2. Power supply such as Thornton Associates #VPS-300.
3. Field-mapping board shown in Figures 18 and 19: drilled plywood board on legs; wire is enameled copper, 20 gauge or heavier.
4. Compass.
5. Iron filings.
6. Two bar magnets and soft-iron bar of same size.
7. Notched magnet for breaking.
8. Spring balances.
9. Fishline.
10. Ammeter, multiscale, 15A max., low range ~ 1A.

CONTENTS

I INTRODUCTION

This module is primarily about the spectral properties of light and the use of spectrophotometric analysis in science and technology. The laboratory apparatus is a flexible, educational spectrophotometer which is essentially a two-dimensional optical bench on which various optical systems can be constructed and studied.

In Section A the qualitative ideas of light transmission and absorption are introduced using colored filters and the eye as the detector. The electromagnetic spectrum is then discussed along with the wavelength specification for radiation.

Section B concentrates on the characteristics of the dispersive elements, prisms and gratings. The differences in dispersion by the two elements are observed and measured, and then explained in terms of the wave theory of light, particularly refraction and diffraction.

Section C puts the ideas of Section A and B together. The student builds a relatively accurate spectrophotometer, calibrates it, and uses it to accurately measure the transmission spectrum of a didymium glass filter. Any one of several optical systems can be used. The qualitative and quantitative applications of spectrophotometers are then discussed and various spectrophotometer specifications, such as resolution, are explained.

II SPECIAL PREREQUISITES

There are no special prerequisites for this module, except that for the Physics of Technology series as a whole: high school algebra.

III TABLE OF CONTENTS OF THE MODULE

Preface
Introduction
  Why Study Spectrophotometers?
  What Will You Learn?
  Goals

SECTION A: Measuring Light Absorption

What Is A Spectrophotometer?
Spectrophotometer Components
Experiment A-1. The Light Source
Experiment A-2. A Simple Spectrophotometer
Setting Up A Grating Spectrophotometer
Setting Up A Prism Spectrophotometer
Transmission And Absorption
Analysis Of Your Transmission Spectra
The Electromagnetic Spectrum
Review
Questions

SECTION B: The Dispersion Of Light

What Is Dispersion?
Dispersive Elements
Experiment B-1. The Spectrum From A Diffraction Grating
Experiment B-2. The Spectrum From A Prism
Experiment B-3. Comparing The Prism And Grating
Experiment B-4. Building A Better Spectrophotometer
Light As Wave Motion
How Do We Describe A Wave?
Wavelength Scales For Light

The Frequency Scale For Light
Analyzing Your Curves By Wavelength
The Physics Of Prisms
The Physics Of Gratings
Review
Questions And Problems

SECTION C: Spectrophotometer Analysis

How Good Is Your Spectrophotometer?
Experiment C-1. Measuring Transmission Spectra
Analyzing Your Data
Application Of Spectrophotometers
Spectrophotometer Quality
Spectrophotometer Specifications
Other Spectrophotometer Systems
Review
Questions

IV GOALS

The objectives of the Spectrophotometer module have been included at the begining of the module.

V DISCUSSION OF ACTIVITIES

The module is divided into three Sections, each representing approximately one week's study. It assumes that approximately three class hours and two lab hours will be devoted to each section. A recommended scheduling of class and lab activities, and content of class periods, is as follows:

First Class Period

This should orient the student to the topics that will be covered in the section and to the experiments that will be performed. It should include background material, for example a short film about the topic, and a discussion of the lab experiments and apparatus that will be used.

Laboratory Session

The laboratory experiments should be done before the week's final two class sessions. They generally can be done in a two-hour lab period, though slower-working students may take somewhat longer.

Second Class Period

This should discuss the laboratory activities and the data taken. The students should be helped in graphing and analyzing their results and in understanding the behavior in terms of the underlying physical laws or principles. If the optional experiments were not done by the students, they can be done here as demonstrations. Problems and questions can be assigned at this time.

Third Class Period

This should continue the discussion of the physics underlying the device behavior. The assigned Questions and Problems can also be discussed. It is often a good idea to end this class with a short 20-minute quiz on the section's work.

The following are specific notes and suggestions relating to each section:

SECTION A

This section introduces the basic components of spectrophotometers and the use of spectrophotometers in qualitative measurements. In the experiments the students build simple spectrophotometers using a prism or grating and their eye as the detector. They then make visual estimates of the transmission spectra of various colored filters. The inaccuracy of the measurements is tolerable since the goal is for the students to gain a general understanding of spectrophotometric analysis.

It is sometimes difficult to get students to estimate carefully. They are often uneasy at the inaccuracy of the procedure. It is helpful to remind them to squeeze the greatest practical accuracy out of the procedure.

In the lab, draw attention to the similarities and differences between the appearance of the spectra produced

by the prism and grating. This will set the stage for the next section.

Using incense smoke inside the spectrophotometer box to make the light paths visible is quite effective. Light the incense with a flame and let it burn several seconds to get hot. Then extinguish the flame and place the incense on an ashtray or metal pan near the optical path. The incense gets quite hot, so the ashtray is important. Close the cover and wait a minute for smoke to appear. Blow or fan air in one of the holes briefly to distribute the smoke more evenly. If the smoke gets too dense and absorbs too much of the beam, this can be easily remedied by opening the top part way.

What you see is light scattered from micro-sized droplets of condensed, partly oxidized hydrocarbons. Scattering is greater in the forward direction and for shorter wavelengths. Thus the beam is most vivid when viewed coming toward you. Also, the smoke acts like a weak yellow filter since it selectively removes blue.

It is important throughout this module to permit the students to "play" and explore, particularly during the begining of the lab. The apparatus is flexible and can be used in many ways for learning, and many striking results can be obtained.

NOTE: The gratings and front surface mirrors can be cleaned by flushing them with alcohol or other mild organic cleaner and "scrubbing" the surface very lightly with a cotton ball or camel hair brush. Even with the greatest care, you shouldn't repeat this too often.

The smoke from the incense may also leave a deposit on the clear plastic cover. This too can be cleaned with alcohol. Do not use acetone or other solvents since they may disolve the plastic.

SECTION B

In this section students build a simple spectrophotometer to study the dispersive elements--prisms and gratings. In the experiments, the relative displacement of each color is measured. When the colors are translated into wavelengths, the displacements can be graphed as a function of wavelength. The resulting graphs show a linear relation for a grating and a nonlinear relation for a prism.

The physics behind these results is discussed in the module starting with a brief survey of the wave model of light. Refraction and diffraction are then covered to gain an understanding of the causes for the dispersion.

A final experiment with a more accurate optical setup, a photodetector and an amplifier, sets the stage for measuring a complex spectrum (didymium) in Section C.

The first three experiments are not difficult and can easily be finished within an hour, giving time to start on the final experiment. In that experiment students get practice setting up and aligning a relatively accurate spectrophotometer, but the time-consuming data-taking is posponed until the last section.

If time permits, students should be encouraged to try out the spectrophotometer they have constructed. For example, have them put a filter in and scan the spectrum across the exit slit, watching the needle drop when their eyes tell them it should. Students are fascinated with the infrared (the photodetector is sensitive well into the IR, but only slightly into the UV). Ask them how they know IR is striking the detector.

Optical alignment in Experiment B-4 is a bit of a challenge, so teachers should gain familiarity with the equipment beforehand. The instructions are complete but quite detailed, so students often try to skim over them. Errors tend to propagate in optical systems, so it is a good idea to get each component right before moving on to another further along the optical path. The most common source of grief comes from permitting the beam to wan-

der up and down vertically.

SECTION C

This lab requires some care if accurate results are to be obtained. Have the student see the lab notes for Section B for alignment of the spectrophotometer system. The meter must usually be rezeroed between measurements, so it takes time.

The "amount" of light registered by the meter varies with wavelength in a way that depends on the optical alignment, the bulb temperature, and the photodetector response. Thus, the amplifier gain must be adjusted for each wavelength setting. It is assumed in the text that the amplifier has variable gain, so that it can be reset at full scale when the filter is out. While this is convenient, it is not absolutely necessary. That is, the data can be obtained by finding the ratio of the observed readings with and without the filter.

There are advantages in having different students use different optical layouts. Three optical systems are discussed on pages 66 and 67. Have students compare their results for the various spectrophotometers in terms of range, resolution, and accuracy.

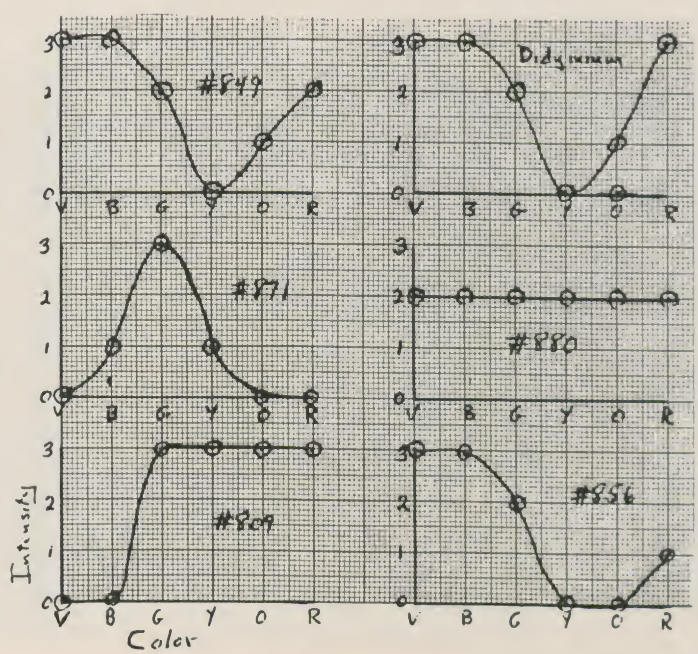
VI SAMPLE DATA

SECTION A

Typical data for Experiment A-2 are shown in the graph. There is no difference between the grating and prism results since neither absorbs significant amounts of any color. The only difference is in their dispersion. Do not be concerned if not all the students' estimates agree. Instead use their differences as an argument for more objective and quantitative methods for measuring light intensity.

The most significant information is derived in a series of questions on pages 14 and 15. It is important that students complete these questions thoughtfully and that the results are discussed. The answers to these questions are:

1. b
2. a or b
3. c
4. e
5. b
6. b
7. c
8. d
9. False
10. True
11. True
12. c
13. True



SECTION B

Dispersion Calculation

Grating:

400nm $\underline{D} = \dfrac{69\text{-}0\text{mm}}{360\text{-}730\text{nm}} = -.19\ \dfrac{\text{mm}}{\text{nm}}$

550nm $\underline{D} = \dfrac{69\text{-}0\text{mm}}{360\text{-}730\text{nm}} = -.19\ \dfrac{\text{mm}}{\text{nm}}$

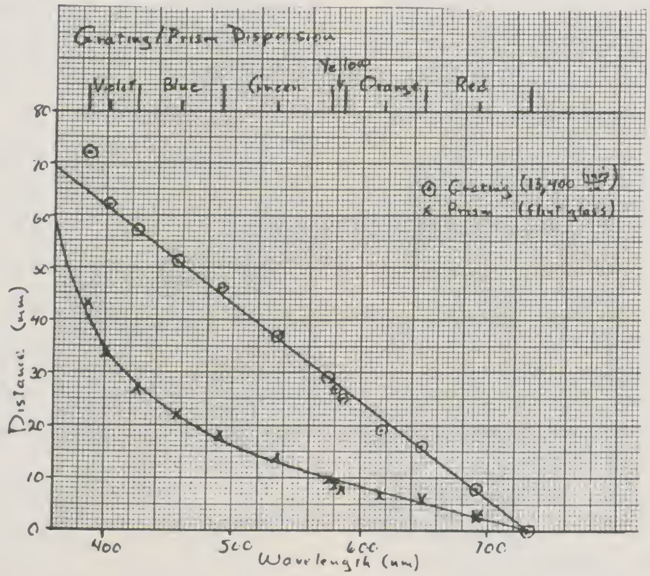
700nm $\underline{D} = \dfrac{69\text{-}0\text{mm}}{360\text{-}730\text{nm}} = -.19\ \dfrac{\text{mm}}{\text{nm}}$

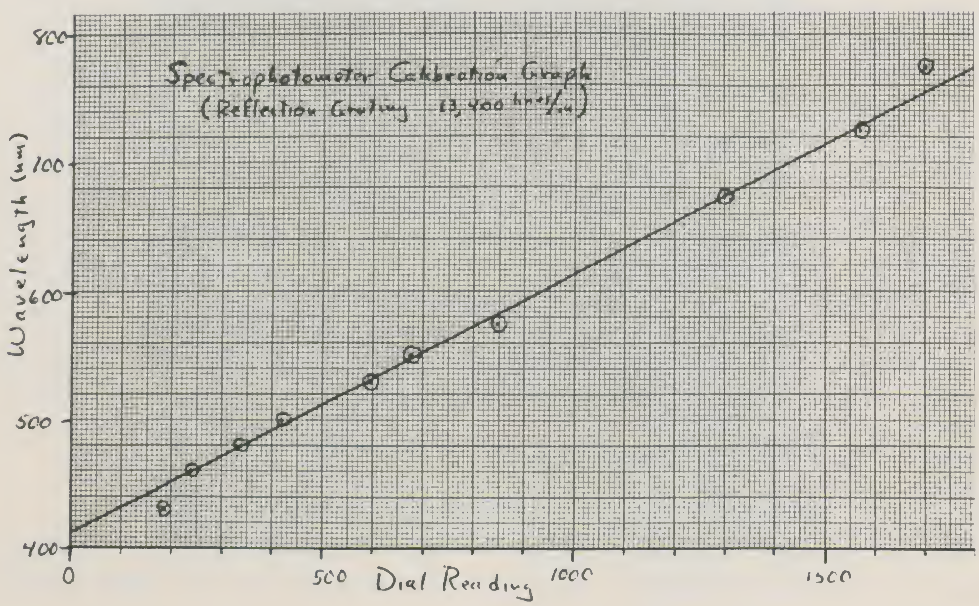
Prism:

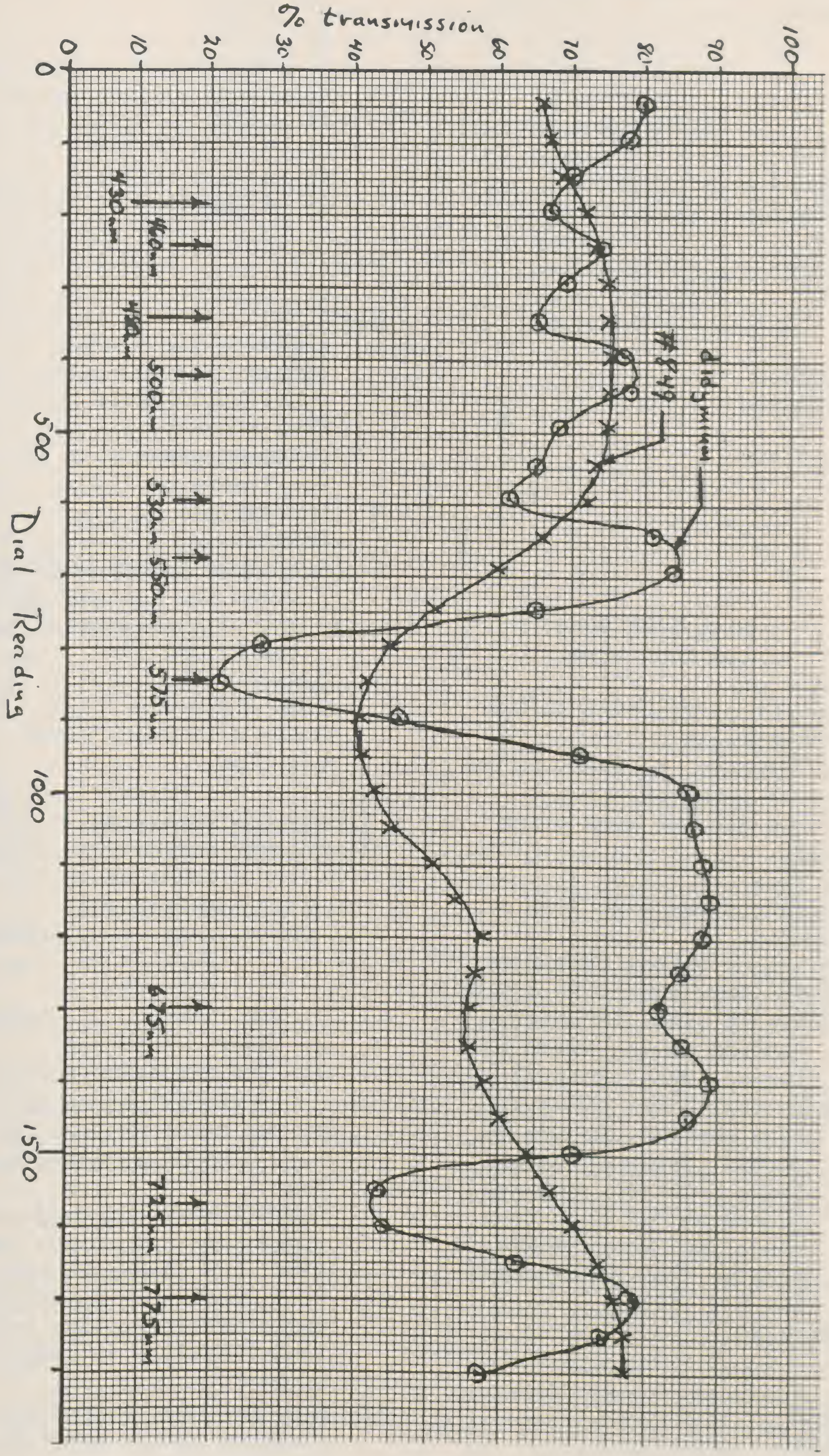
400nm $\underline{D} = \dfrac{50\text{-}0\text{mm}}{360\text{-}488\text{nm}} = -.39\ \dfrac{\text{mm}}{\text{nm}}$

550nm $\underline{D} = \dfrac{26\text{-}0\text{mm}}{360\text{-}700\text{nm}} = -.076\ \dfrac{\text{mm}}{\text{nm}}$

700nm $\underline{D} = \dfrac{21\text{-}0\text{mm}}{360\text{-}730\text{nm}} = -.056\ \dfrac{\text{mm}}{\text{nm}}$






% transmission
0
10
20
30
40
50
60
70
80
90
100
Dial Reading
0
500
1000
1500
didymium
#849
430nm
460nm
480nm
500nm
530nm
550nm
575nm
675nm
725nm
775nm

VII SOLUTIONS TO PROBLEMS AND QUESTIONS

SECTION A

Questions

1. a) blue
   b) red
   c) nothing
2. A blue
   B yellow
3. D and E
4. green
   yellow
5. light source
   monochromator
   sample
   photodetector
   display

SECTION B

Questions

1. Prism - blue bent more.
   Grating - red bent more.
2. Yes - grating.
3. The index of diffraction varies with wavelength.
4. Grating (depends, however, on the number of lines per inch).
5. In the blue for the data given earlier.
6. A - not at all.
   B - constant dispersion like a grating.
   C - dispersion varies from 0 at short wavelengths to a high value at long wavelengths.
7. Prism: depends on the prism material; see Figure 25.
   Grating: No real limit since the line spacing, a, can be varied. There are practical problems, however, in making "a" less than about 1μm, which means λ greater then 10nm (assuming $\theta \sim .01$).
8. See Figure 39.

Problems

1. a) 358nm
   b) 640nm
   c) 481nm
   d) 430nm
   e) 170nm
   f) 385.41nm
2. a) 4310Å
   b) .431μ
   c) 4.31×10^{-5}cm
   d) 4.31×10^{-7}m
   e) 431mμ

SECTION C

Questions

1. slits
   lenses
   spherical mirrors
   flat mirrors
   prism or grating
2. See Figure 56.
3. Refraction.
   Prism.
4. All other things being equal, the wider the slit, the more overlapping of the images of each color. See Figure 70.
5. linearity
   high dispersion
   broad wavelength range
   low cost
6.

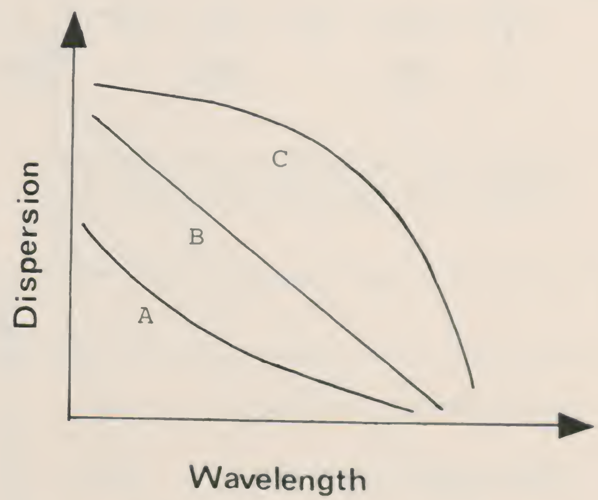
	Prism	Grating
linearity:	nonlinear	linear
dispersion:	depends on index of refraction	depends on line spacing
range:	limited, depends on material	almost unlimited
cost:	lower	higher

7. a) poor resolution.
   b) low intensity for the same resolution as an equivalent slit.
   c) no other pattern has less overlap of wavelengths.
8. Yes.
9. Doesn't make any difference provided that all colors have the same path length through the sample.
11. Bolt components rigidly to the base
    Use a better quality grating
    Insert baffles to reduce stray light
12. B - the poor resolution of the instrument simply smeared out the features.

VIII POST-TESTS

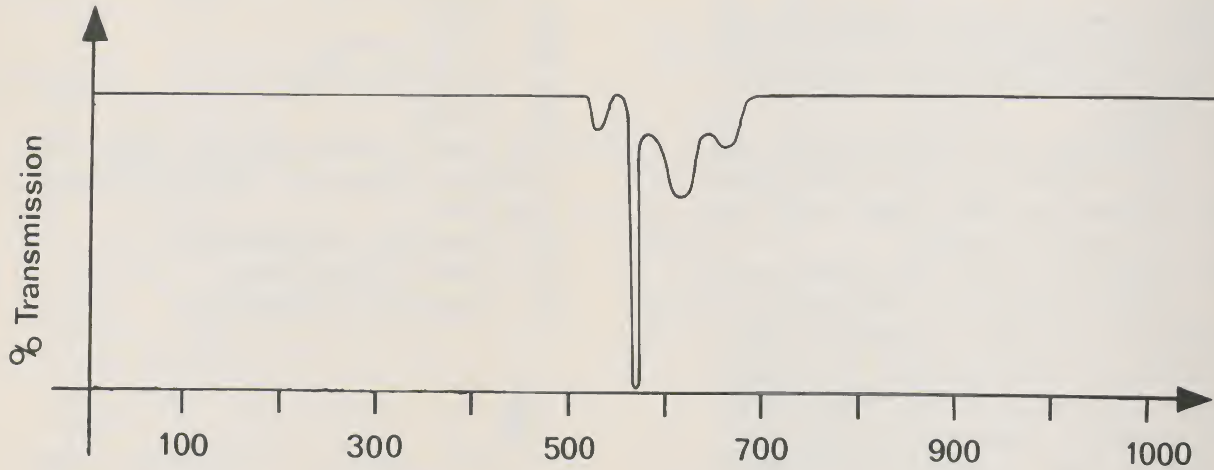
Test I

1. Would the following applications use spectrophotometers for qualitative or quantitative analysis or both?
   a) Checking for the presense of pollutants in drinking water.
   b) Measuring the sugar level in a person's urine.
   c) Finding which of several pale blue filters is didymium.
2. Suppose you had a "tuneable dye laser"--a device which will produce any color in the spectrum. What other components would you need to make a spectrophotometer using this laser?
3. Describe two ways of finding the light path through a spectrophotometer. Which would be best for an expensive system?
4. Sketch the absorption spectrum of a red filter.
5. What color is light of the following wavelengths:
   a) 700nm
   b) 400nm
   c) 370nm
6. What are the fundamentally similiar properties of light, radio waves, and x-rays?
7. Which of the following wavelength radiation would be visible:
   a) 50nm
   b) 500nm
   c) 5,000nm
   d) 50,000nm
8. Which of the following can be observed in both light and other waves:
   a) Bending of a wave around an object
   b) Up and down motion of a wave
   c) Bending of a wave front when it changes speed
   d) Two different waves combining to give no waves at certain points
9. A musical tone is exactly 440Hz. On a day when the speed of sound is 350m/sec, what is the wavelength of this tone?
10. Which of the following wavelengths of radiation are visible:
    a) 300Å
    b) $.4 \times 10^{-6}$m
    c) 55.0×10^{-6}cm
    d) 3.34μ
11. The graph shows data on three dispersive elements. Which element has the:
    a) greatest dispersion
    b) least dispersion
    c) constant dispersion



12. a) Which one of the three dispersive elements in the figure above is most like the prism used in the lab?
    b) Which must be a grating?
13. A grating having 8500 lines per cm diffracted yellow light through an angle of exactly 30°. From this, find the wavelength of yellow light.
14. Suppose you were given a solution and asked to find which 5 of 100 possible compounds (with known spectra) were in the solution. How would your procede? What difficulties might you have?
15. Suppose that 10g of a given substance dissolved in water transmits 50% of the light at 650nm. How much of the substance is present in a solution that transmits:
    a) 25% of the light at 650nm?
    b) 70% of the light at 650nm?

16. You work in a lab that needs to buy a spectrophotometer to determine within 1% the amount of a substance with the following spectrum:

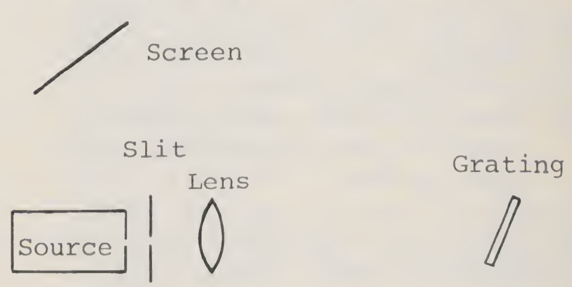


Which of the spectrophotometers (A-D) with specifications given in the table below will do the job most cheaply?

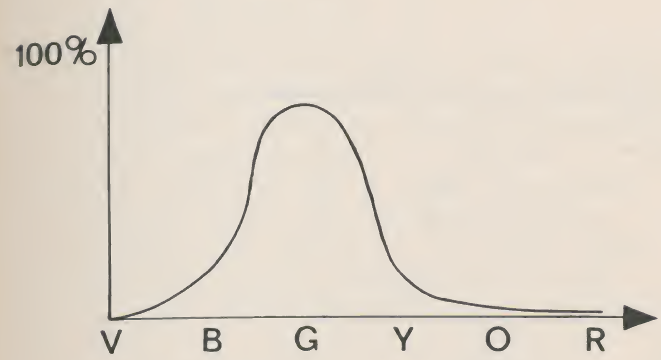
	A	B	C	D
Photometric Accuracy	1%	1%	1%	5%
Wavelength Accuracy	.1nm	1nm	10nm	50nm
Resolution	1nm	1nm	5nm	50nm
Range	100-500nm	200-1000nm	500-700nm	300-700nm
Cost	$1,000.00	$8,000.00	$3,000.00	$2,000.00

Test II

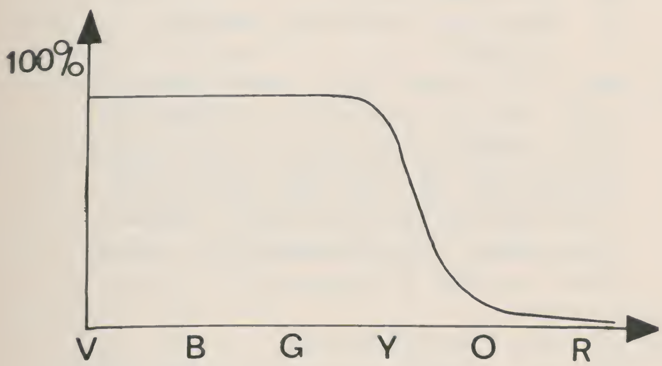
1. Would the following spectrophotometer applications use qualitative or quantitative analysis or both? Explain.
   a) Determining the elements present on Mars from its light spectrum.
   b) Matching oil from a suspect's hand to oil in a stolen car motor using the oil's spectrum.
   c) Measuring the concentration of alcohol in beer.
2. What would be the effect of using a red bulb as a source in a spectrophotometer system?
3. Describe how you would align the following spectrophotometer.



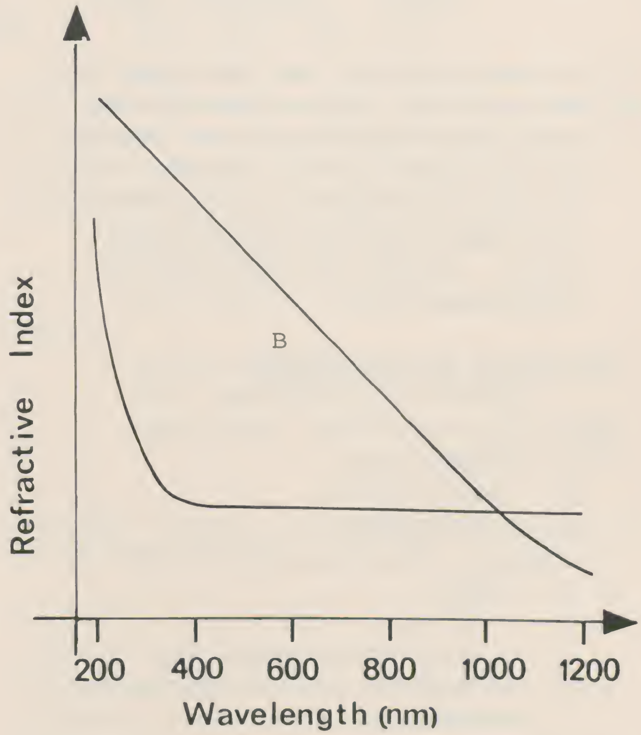
4. What color filters would yield the following spectra:
   a) Transmission



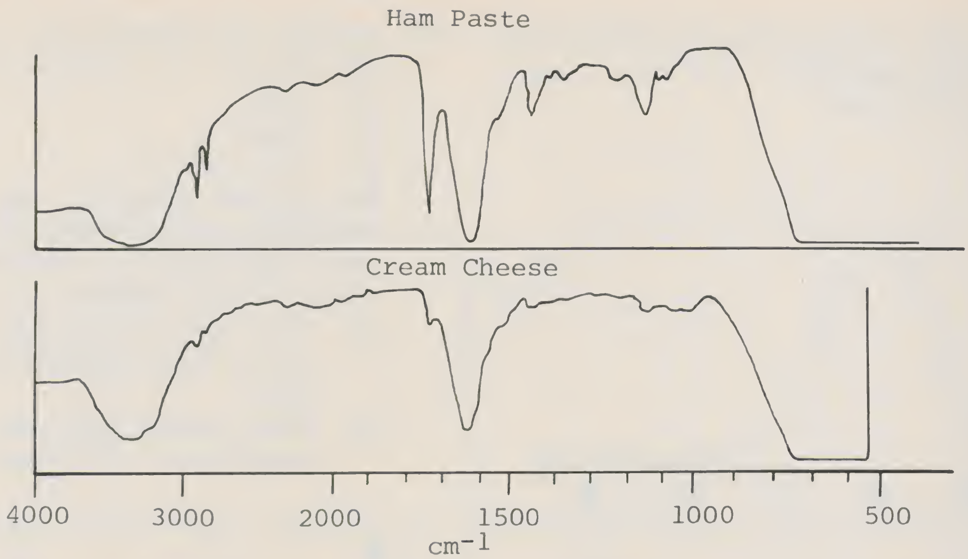
   b) Absorption



5. At approximately what wavelength would the following spectral colors fall?
   a) Greenish
   b) Yellow-green
6. In what fundamental ways are gamma rays, visible light, and infrared radiation different?
7. Would the following wavelengths fall in the visible, infrared, or ultraviolet?
   a) 3nm
   b) 30nm
   c) 300nm
   d) 3,000nm
   e) 30,000nm
8. List three properties of light which are shared by water waves.
9. What is the frequency for far infrared radiation with a wavelength of 100,000nm?
10. Convert to nanometers:
    a) 3801Å
    b) 1.01μ
    c) 318μm
    d) $.38 \times 10^{-6}$m
11. Two prisms, A and B, are made from materials whose index of refraction dependence on wavelength is given in the figure:
    a) Over what wavelength range would each prism be most useful?
    b) Which would give the greatest dispersion at 300nm?



12. Explain how you could determine whether the dispersion of a grating was constant.
13. The red (700nm) in the second order of a grating's spectrum overlaps what wavelength from the third color?
14. The absorption spectra shown in the figure appeared recently in a popular magazine. Which parts of these spectra do you guess are due to fat? Roughly how much less fat is in cream cheese?

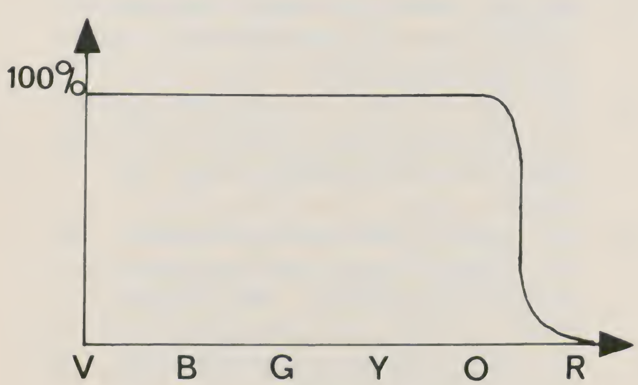


15. How much A is in the unknown?
16. Which of the spectrophotometers (A-D) with specifications given in the table is the cheapest instrument that will do satisfactory quantitative analysis, accurate to 10%, of substance "A" in Problem 15?

Solutions To Post-Tests

Test I

1. a) Qualitative
   b) Quantitative
   c) Qualitative
2. Sample, Detector, and Display
3. a) Smoke
   b) Following with a card
   c) A card since smoke will leave a deposit on the expensive components
4. Absorption



5. a) Red
   b) Greenish blue
   c) Black or invisible (ultraviolet)
6. They all three share wave properties such as reflection, refraction, diffraction, and interference and travel at the same speed (3 x 10^8 m/sec in a vacuum). (Note: the answer "electromagnetic radiation" is not a property.)
7. b only
8. a) yes (diffraction)
   b) no (can't observe light waves)
   c) yes (refraction)
   d) yes (interference)
9. $\lambda = c/f = 350/440$ Hz $= .796$m
10. a) no
    b) yes
    c) yes
    d) no
11. a) C (at long wavelengths)
    b) C (at short wavelengths)
    c) B
12. a) A
    b) B
13. $a = 1/8{,}600$cm
    $\lambda = a\sin\theta = \sin 30/8{,}600 = 582$nm
14. So many combinations exist that you are in deep trouble unless each of the 100 compounds has a unique "signature" in its spectrum--easily distinguished fine structure such as the two sharp absorption peaks at 575 and 585nm of didymium.
15. a) 20g

16. C

Test II

1. a) Qualitative
   b) Qualitative
   (Both is acceptable if the student explains the possiblity of measuring oil additive concentrations.)
   c) Quantitative
2. A red bulb would limit the spectral range of the spectrophotometer to the red. (In fact some light of all wavelengths would come from most red bulbs; still, the low intensity in the blue would limit the spectrophotometer usefulness there.)
3. See the alignment checklist in the module.
4. a) Green
   b) Orange
5. a) 475nm
   b) 575nm
6. Their wavelengths are different (approximately 10^{-3}nm, 500nm, and 10^{4}nm, respectively), and they interact with different types of matter.
7. a) UV
   b) UV
   c) UV
   d) IR
   e) IR
8. Reflection, refraction, diffraction, and interference.
9. $f=c/\lambda=3\times10^{8}\text{Hz}/10^{-4}\text{m}=3\times10^{12}\text{Hz}$.
10. a) 380.1nm
    b) 1,010nm
    c) 318nm
    d) 380nm
11. a) A:200-400nm b) A
    B:200-1,200nm
12. Measure the location of various colors in a spectrum produced by the grating. Graph these locations against the wavelength of the colors. A straight line indicates constant dispersion.
13. We want to know λ_x where: $\sin\Theta = 2\lambda_{red}/a=3\lambda_x/a$
    Since a and Θ are constant, we have: $\lambda_x=2/3\ 700=467$nm (greenish-blue)
14. a) Bumps at 1,150; 1,470; 1,750; double bump at 2,900cm^{-1}
    b) Roughly 3 times
15. 20g
16. D

IX LIST OF APPARATUS

The apparatus specifically designed for this module is an educational spectrophotometer (Model ESP-300) manufactured by:

Thornton Assoc., Inc.
87 Beaver Street
Waltham, Mass. 02154
Tel: (617) 899-1400

However, most of the experiments of Sections A and B can be performed with a conventional optical light source on a flat surface. The necessary optical components are available from:

Edmund Scientific Company
701 Edscorp Building
Barrington, New Jersey 08007

and:

Ealing Corporation
2225 Massachusetts Avenue
Cambridge, Massachusetts
02140

Catalog numbers are indicated where appropriate.

SECTION A

Slits (2): Made from two double-edged razor blades, slit width = 1mm
Achromatic Lens: d = 36mm
f = 87mm
Edmund #6408
Diffraction Grating: Cut from sheet of Edmund #50,201 grating material and mounted on a flat microscope slide
Filter Book: Edmund #40,675
Didymium Filter: Ealing #26-5686
Prism: Edmund #30,143
Plane Mirror (2): Edmund #40,773

SECTION B

Same as Section A plus:

Spherical Mirror (2): $\underline{d}$ = 50mm
$\underline{f}$ = 87mm
Ealing #23-5283

Photometer:

SECTION C

Educational Spectrophotometer must be used.

CONTENTS

I INTRODUCTION

In this module, the stroboscope is used in laboratory experiments on kinematics and dynamics. In this case, the title device is used in making measurements, but the physics of the device itself is not studied. This represents a deviation from the usual Physics of Technology approach in which the physics of a device is studied. This departure was permitted because there is no single common device, both familiar and interesting to the students, whose physical analysis could serve as the basis for a compplete treatment of the principles of kinematics and dynamics in a module of acceptable length. In view of the time pressures faced by instructors in covering important topics, it would not be appropriate to spread the study of kinematics and dynamics over two or more modules such as "The Air Track" and "The Falling Projectile". Nor would these module topics be of as much interest to the student as the stroboscope. For these reasons, it was felt that an exception to the rules was warranted.

II PREREQUISITES

There are no prerequisities for this module other than that of high school algebra.

III TABLE OF CONTENTS OF THE MODULE

IV LEARNING OBJECTIVES

This list of objectives indicates what the student should be able to do after completing the study of this module.

Section A

1. Define the following:
   (a) Stroboscope
   (b) Tachometer
   (c) Velocity
   (d) Acceleration
   (e) Uniform Acceleration
2. Describe how the stroboscope causes a reference mark on a rotating object to seem to stop. Include sketches.
3. State the two rules relating the number of stationary images to the flash rate and the rate of rotation of the object.
4. Given the number of images and the flash rate at which each set of images is formed, determine the rate of rotation for vibration of an object.
5. Describe three applications of the stroboscope.
6. Given a strobe photo of an object moving along a line parallel to a reference scale which can be used to measure distances, and given the flash rate of the strobe, construct a position-time graph for the motion.
7. Calculate the average velocity during a specified time interval from information available from any of the following: a strobe photo, a table of values of position and time, or a position-time graph.
8. Construct a velocity-time graph from any of the following: a strobe photo, a table of values of position and time, or a position-time graph.
9. Calculate the average acceleration during a specified time interval from any of the following: a strobe photo, a table of values of velocity and time, or a velocity-time graph.
10. Construct an acceleration-time graph from any of the following: a strobe photo, a table of values of velocity and time, or a velocity-time graph.
11. Determine the slope and intercept of a straight-line graph, and write the equation of the line.

Section B

12. Write the basic equation of kinematics and state the meaning of each symbol; the equations are:

$$\underline{v}_{av} = \frac{\Delta \underline{x}}{\Delta \underline{t}}$$

$$\underline{a}_{av} = \frac{\Delta \underline{v}}{\Delta \underline{t}}$$

For constant acceleration:

$$\underline{v} = \underline{v}_o + \underline{at}$$

$$\underline{x} = \underline{x}_o + \underline{v}_o\underline{t} + \tfrac{1}{2}\underline{at}^2$$

13. Recognize a situation where one of the above equations applies, and if given the value of all but one of the quantities in that equation, solve for the unknown.
14. State the value of acceleration due to gravity in both the SI and the British system of units.
15. Given the magnitude and direction of the initial velocity of an object in free fall, determine the horizontal and vertical components of displacement and velocity at any specified time.
16. Use the equations of kinematics to solve problems in projectile motion under gravitation (e.g., given the horizontal and vertical distance which the projectile is to cover, and the angle of the intial velocity, what initial velocity is necessary, or if given the initial velocity and the initial distance fallen, what will be the horizontal distance covered?)
17. Given any two of the following three quantities, determine the remaining quantity: the mass of an object, the resultant force acting on the object, the acceleration of the object.
18. Given either the mass or the weight of an object, determine the other.
19. State and use Newton's third law of motion.
20. Calculate the acceleration of an object on a frictionless inclined plane if the angle is given.
21. Given quantities such as force or velocity which have direction,

resolve them into horizontal and vertical components.

22. Define terminal velocity. Explain why an object falling through a fluid will reach a terminal velocity.
23. Describe a method for determining the motion of an object acted upon by a velocity-dependent force. Assume that you have a graph which shows how the force depends on velocity.
24. Given the weight and initial velocity of an object falling through a fluid, and a graph which shows how the force depends on velocity, calculate the acceleration, velocity, and position at a specified time.
25. Describe the type of force needed to produce simple harmonic motion.
26. Define "period" and "amplitude" for simple harmonic motion.
27. List three basic features of simple harmonic motion.

V DISCUSSION OF ACTIVITIES

The module is divided into three sections, with experiments in each section to provide the basis for discussion of physical principles.

Section A introduces the stroboscope through its use as a tachometer and develops graphical techniques for describing and analyzing motion in one dimension, with minimum algebraic development. The instructor may want to introduce the topic of parallax and its effect upon the measurements in this module, since the module does not deal with it. Care should be exercised if power tools are used in Experiment A-1. For instance, if a saw is used, the blade should be removed and the saw should be clamped and shielded.

Section B develops the algebraic approach through use of the standard equations of kinematics. Motion in a plane and projectile motion are also treated.

Section C develops Newton's laws of motion. Because the concept of frames of reference is not emphasized, we have chosen to justify Newton's First Law as a special case of the Second Law. If the class is capable of a more advanced treatment, you may want to introduce the concept of frame of reference and discuss the role of the First Law as the criterion for a frame to be inertial. Also included in Section C is a treatment of velocity-dependent forces which can provide an exposure to simple iterative computer techniques, which is not usually possible in an introductory course. A brief introduction to Simple Harmonic Motion is also included as an example of position-dependent forces.

For many classes, the instructor may find that more than three weeks could be required to cover the entire module. If this is the case, one or more of the topics in Section C may be omitted.

The module was written for students having no experience with the vector concept. In the case of a class that has had more exposure to vectors, the instructor may want to make more use of vectors than is done in the module.

<u>Time Estimates for the Experiments</u>:

Exp. A-1	Observing Repetitive Motion	60 min.
Exp. A-2	Observing Translational Motion	90 min.
Exp. B-1	Using the Stroboscope to Study Translational Motion	90 min.
Exp. B-2	Motion in a Plane	90 min.
Exp. C-1	Force, Mass, and Acceleration	90 min.
Exp. C-2	Velocity-Dependent Forces	90 min.
Exp. C-3A	Elastic Forces	45 min.
Exp. C-3B	Simple Harmonic Motion	30 min.
Exp. C-3C	Another Position-Dependent Force	60 min.

If this exceeds the laboratory time available, you may choose to do some of the experiments as demonstrations. However, at some point early in the study of the module, the student should get his hands on a stroboscope and use it as an aid in observing motion.

The following pages provide possible

formats for data sheets and sample data for each of the experiments.

VI SAMPLE DATA AND QUESTION ANSWERS

Exp. A-1

(Data taken with automotive heater motor.)

5. Yes, there is more than one flash rate producing one image; the highest flash rate with one image is 3840 fpm.

fpm	# of images
635	1
730	1
930	1
1260	1
1920	1
3840	1
7610	2
15,200	4

6. Two lines, on opposite sides of disc.

7. Four lines, at 90° intervals.

Question 1:

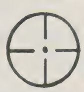
The strobe is flashing at once per revolution at 3840 fpm and gives one stationary image. At 7610 fpm, the strobe is flashing at twice per revolution and thus gives images 180° apart on the disc. We can see that it is rotating at 3840 since there are no greater flash rates producing a one-line image.

8.

fpm	n
1420	3
2310	3
1980	4
2920	4

3 images

4 images



9. For three images, the mark moves some integer multiple of 120° between flashes, and for 4 images, the mark moves a multiple of 90° between flashes.

Exp. A-2

1. The air track is level if an air cart placed on it in any position does not move in either direction.
3. (a) accelerates
   (b) accelerates slower than a
   (c) accelerates faster than b
4. The glider speeds up faster with a heavier weight, or lighter glider.

5/6.

	time (sec)	distance	average velocity
small glider, 10 g on hanger	1.93	88 cm	46 cm/sec
large glider, 10 g on hanger	5	100 cm	20 cm/sec
large glider, 20 g on hanger	3.45	100 cm	29 cm/sec

7. More information is needed. Speed changes.
9. As the motion goes on, the glider covers larger and larger distances between flashes.

10. One knows the time between flashes and the photograph gives distance covered; therefore, the average velocity can be calculated.

Exp. B-1

1/4. Flash rate: 300 fpm.
Level air track with no accelerating force.

time	position	average velocity
.0	0.0 cm	******************
		14.2 cm/sec
.2	14.2 cm	
		14.3 cm/sec
.4	28.5 cm	
		14.1 cm/sec
.6	42.6 cm	
		14.2 cm/sec
.8	56.8 cm	
		14.3 cm/sec
1.0	71.1 cm	
		14.1 cm/sec
1.2	85.2 cm	
		14.1 cm/sec
1.4	99.3 cm	
		14.3 cm/sec
1.6	113.6 cm	
		14.3 cm/sec
1.8	127.9 cm	
		14.1 cm/sec
2.0	142.0 cm	******************

2/4. Flash rate: 1200/min. for gravitational acceleration.

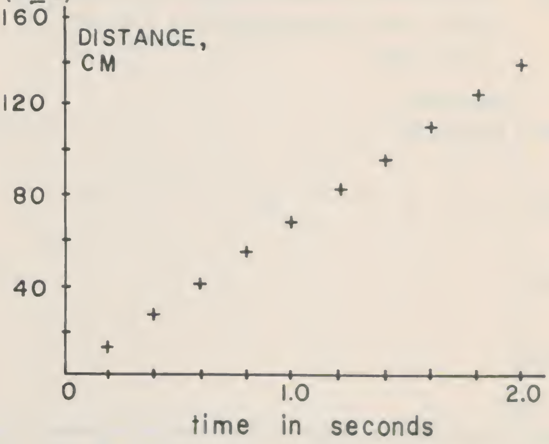
time	position	average velocity
0	0 cm	
		76 cm/sec
0.05	3.8 cm	
		128 cm/sec
0.10	10.2 cm	
		176 cm/sec
0.15	19.0 cm	
		256 cm/sec
0.20	31.8 cm	
		268 cm/sec
0.25	45.2 cm	
		330 cm/sec
0.30	61.7 cm	
		376 cm/sec
0.35	80.5 cm	
		432 cm/sec
0.40	102.1 cm	
		498 cm/sec
0.45	127.0 cm	
		508 cm/sec
0.50	152.4 cm	

2/4. Equation relating force, mass, and acceleration: $\underline{F} = \underline{ma}$.
Flash rate: 600/min.
Result for Tilted Method, 5.7°

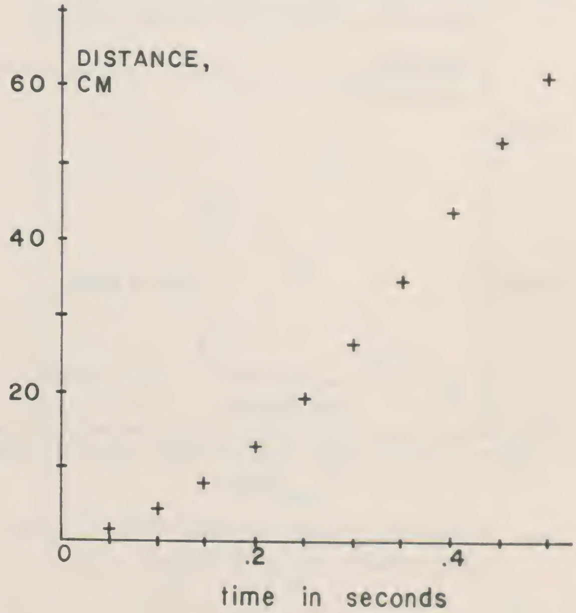
time (sec)	position (cm)	velocity (cm/sec)
0.1	1.3	
		25
0.2	3.8	
		30
0.3	6.8	
		41
0.4	10.9	
		48
0.5	15.7	
		56
0.6	21.3	
		66
0.7	27.9	
		74
0.8	35.3	
		81
0.9	43.4	
		94
1.0	52.8	
		99
1.1	62.7	
		110
1.2	73.7	
		116
1.3	85.3	
		125
1.4	97.8	
		132
1.5	111.0	

5a. Position-time graph for glider with no accelerating force at 300 fpm. (See next column.)

(5a.)

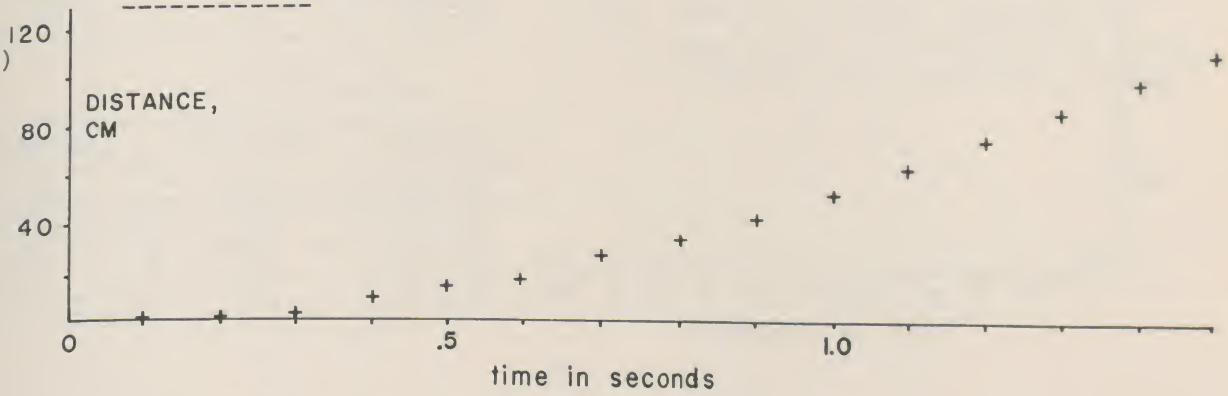


5b. Position-time graph for gravitational acceleration, 1200 fpm.

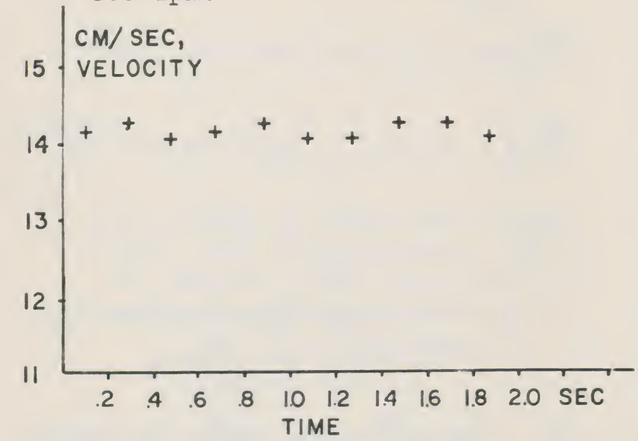


5c. Position-time graph for tilted air track at 600 fpm. (See illustration at bottom of page.)

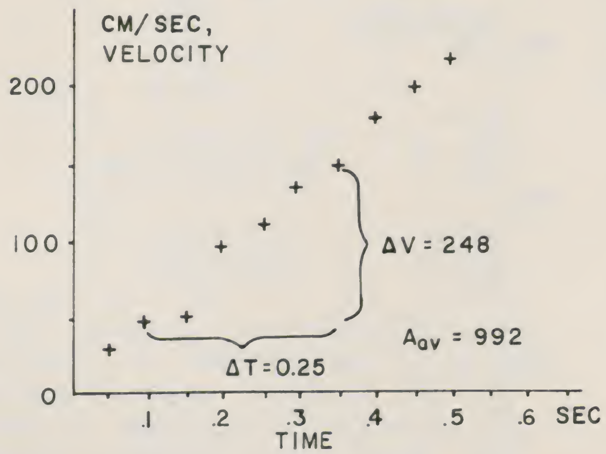
(5c.)



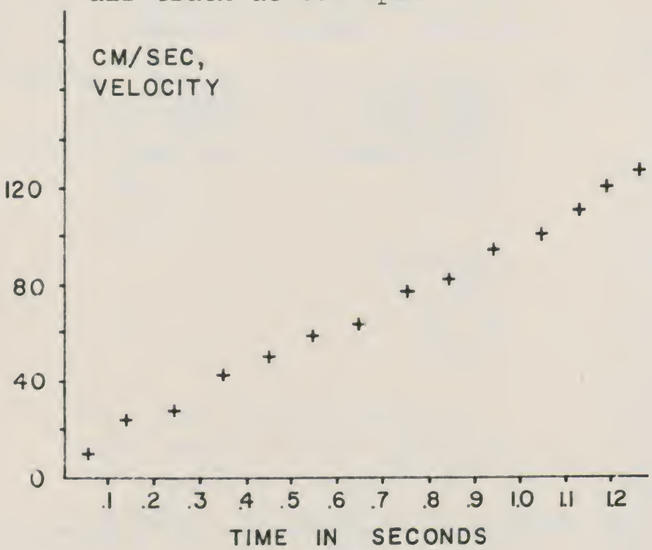
6a. Velocity-time graph for glider with no accelerating force at 300 fpm.



6b. Calculation of acceleration from the velocity-time graph.



6c. Velocity-time graph for tilted air track at 600 fpm.



7. (a) $a_{av} = \frac{V}{t} = \frac{14.2 - 14.1}{1.9 - .1} = \frac{.1}{1.8}$

$\simeq .06$ cm/sec^2 for the constant velocity case.

(b) done on graph of #6b for the acceleration due to gravity.

(c) $A_{av} = \frac{V}{t} = \frac{132 - 25}{1.45 - .15} = \frac{107}{1.3}$

$= 82.3$ cm/sec^2 for the cart on the inclined air track.

8. (a) For the constant-velocity cart, there is no acceleration. Friction will decelerate the cart slightly.

(b) For the gravitational case, the average acceleration is 992 cm/sec^2. It is caused by the earth's gravitational attraction, and its direction is down.

(c) The acceleration on the inclined air track is constant at 82.3 cm/sec^2, and is caused by gravity.

9. a and c are correct, but equation b is completely wrong.

Exp. B-2

3. .05 sec.
4. Flash rate: 1200 fpm.

Horizontal Motion:

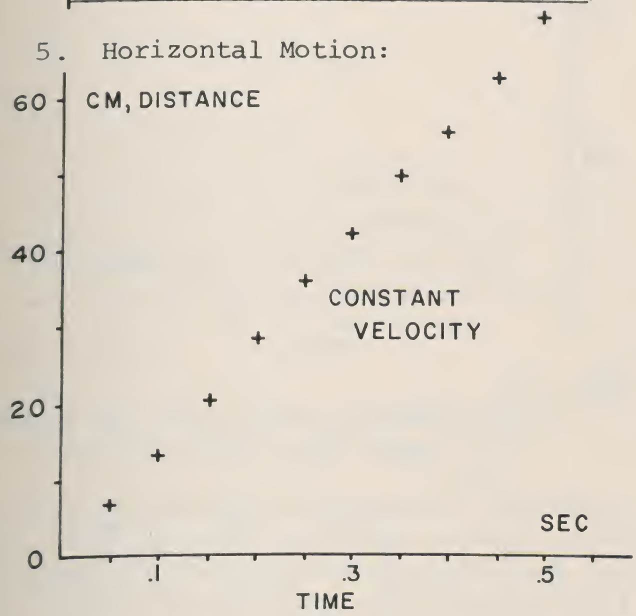
time	position	velocity
0.05	5	
0.10	13	160
0.15	20	140
0.20	27	140
0.25	34	140
0.30	41.5	150
0.35	49	150
0.40	56	140
0.45	63.5	150
0.50	71.0	150

Vertical Motion:

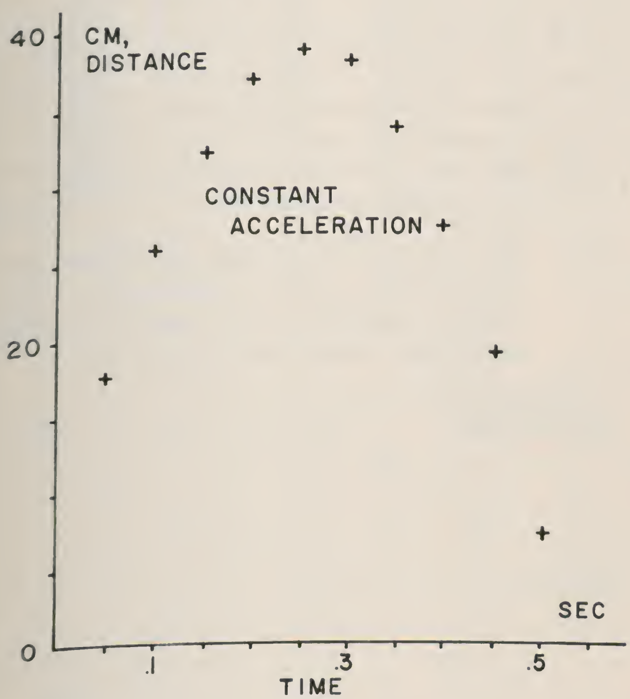
time	position	velocity
0.05	17.5	
0.10	26.5	180
0.15	32.5	120
0.20	36.5	80
0.25	38.0	30

time	position	velocity
0.25	38.0	
		-20
0.30	37.0	
		-70
0.35	33.5	
		-120
0.40	27.5	
		-170
0.45	19.0	
		-230
0.50	7.5	

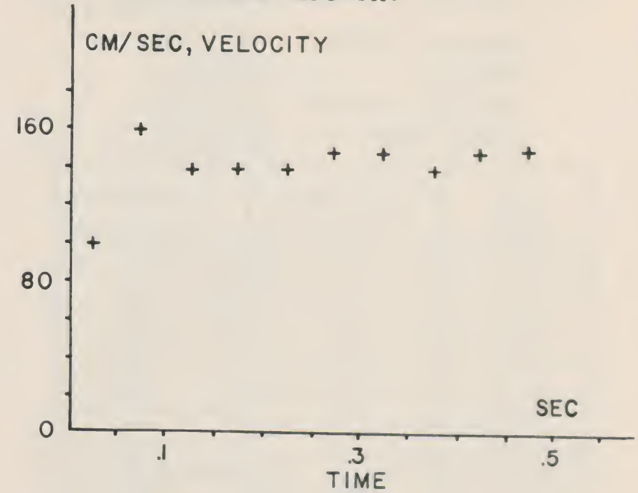
5. Horizontal Motion:



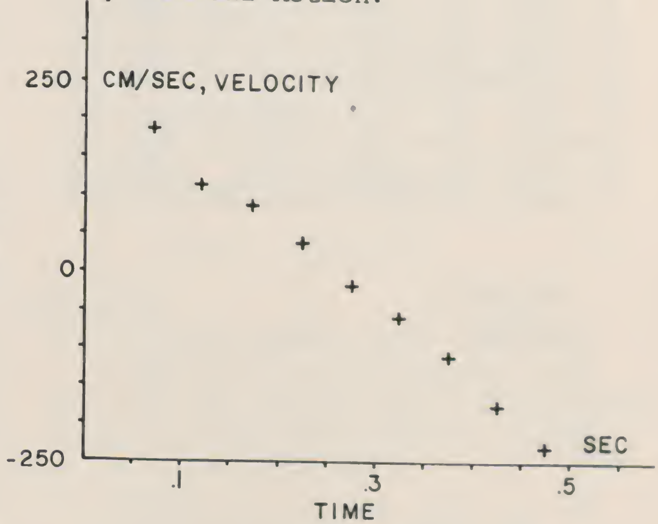
Vertical Motion:



6. Horizontal Motion:



. Vertical Motion:



7. $\underline{S} = \underline{V_o}\,\underline{t} + \frac{1}{2}\,\underline{at}^2$ + constant,

where $\underline{a} = -\underline{g}$

Exp. C-1

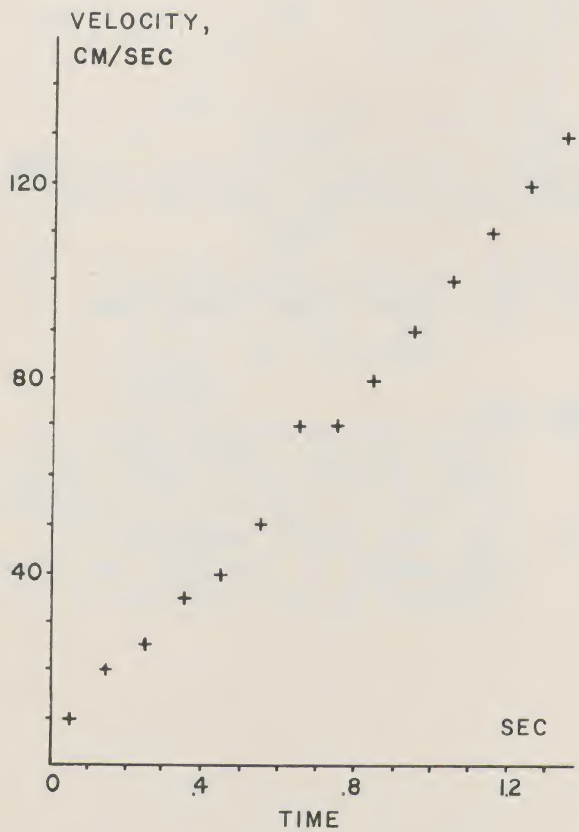
2. On a level air track after one stops pushing, the acceleration is zero if friction is negligible.
3. The 20-g weight suggested in the module is probably too large; a better value would be 5 g.

4. Hanging Weight Method

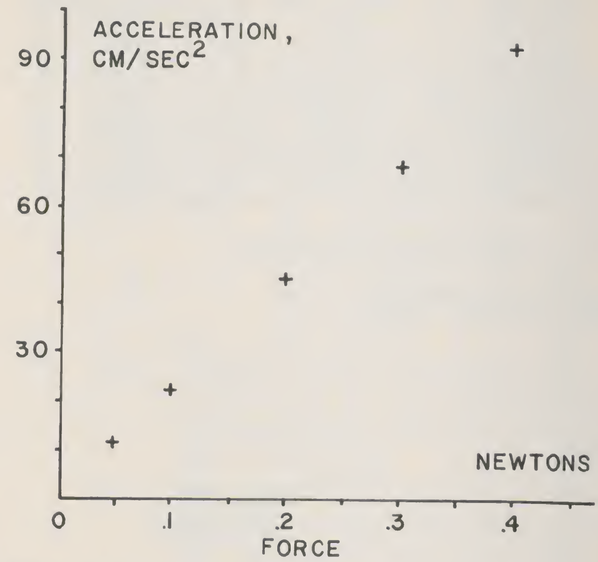
Hanging Mass	.040 kg
Weight	.098 N
Mass of Glider	.39 kg
Flash Rate	600 fpm

time (sec)	position (cm)	velocity (cm/sec)
0	7	
0.1	8	10
0.2	10	20
0.3	12.5	25
0.4	16	35
0.5	20	40
0.6	25	50
0.7	32	70
0.8	39	70
0.9	47	80
1.0	56	90
1.1	66	100
1.2	77	110
1.3	89	120
1.4	102	130

5.



9.

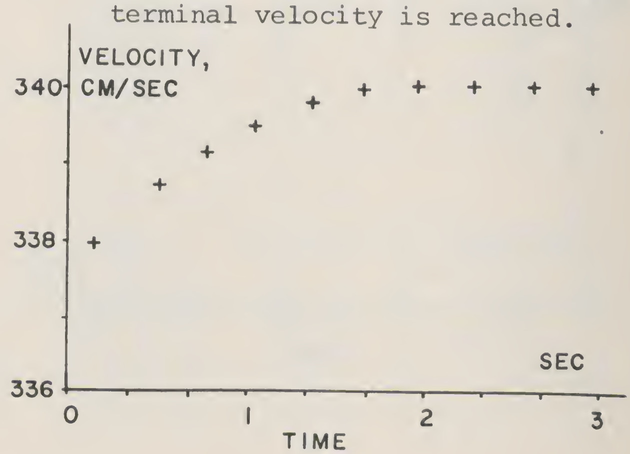


Exp. C-2

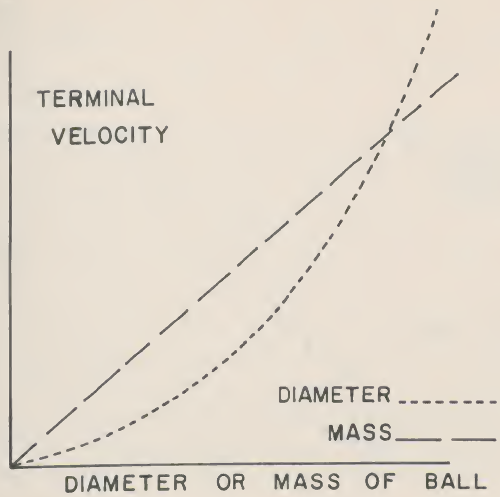
2. ball made of foam, center weighted with lead; dia = 3.67 cm; mass = 1.24 g.

		dist. (cm)	vel.
1	0	0	
2	.03	11.4	379
3	.06	23.0	387
4	.09	34.8	392
5	.12	46.6	395
6	.15	58.5	398
7	.18	70.5	399.5
8	.21	80.7	340
9	.24	90.9	340
10	.27	101.1	340
11	.30	111.3	340

3. The velocity becomes constant at 340 cm/sec. The acceleration becomes constant at 0 cm/sec^2, when terminal velocity is reached.



5.



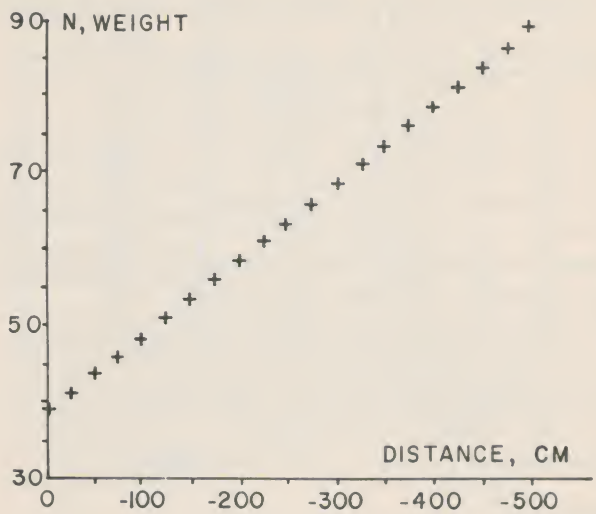
Exp. C-3A

3&

4. This spring was also used for Exp. C-3B sample data.

Mass, g	weight, N	position, cm	dist. stretched, cm
0	0	38.8	0
20	.196	40.4	1.6
40	.392	42.3	3.5
60	.588	44.2	5.4
80	.784	46.5	7.7
100	.980	48.3	9.5
20	1.176	50.4	11.6
40	1.372	52.45	13.65
60	1.568	54.5	15.7
80	1.764	56.55	17.75
200	1.960	58.6	19.8
20	2.156	60.6	21.8
40	2.352	62.7	23.9
60	2.548	64.7	25.9
80	2.744	66.75	27.95
300	2.940	68.75	29.95
20	3.136	70.7	31.9
40	3.332	72.8	34.0
60	3.528	74.9	36.1
80	3.724	76.9	38.1
400	3.920	78.95	40.15
20	4.116	81.0	42.2
40	4.312	83.1	44.3
60	4.508	85.15	46.35
80	4.704	87.2	48.4
500	4.900	89.25	50.45

5.



6. $\underline{F} = -\underline{kx}$

$$\underline{k} = \frac{-\Delta F}{\Delta \underline{x}} = \frac{-508 + 118\ g}{90 - 50\ cm} \times 980\ \frac{cm}{sec^2}$$

$$= +9.6 \times 10^3\ \frac{dynes}{cm}$$

$$= +9.6 \times 10^{-2}\ N/m$$

Exp. C-3B

1. In this sample data, a 300-g mass was the oscillating mass, and the spring from C-3A was used.
3. The flash rate used for sample data was 600 fpm.

spring $\underline{k}$ = $+9.6 \times 10^{-2}$ N/m
= 9.6×10^3 dynes/cm
Equilibrium Position: 68.75 cm

flash no.	time, sec	position, cm	velocity, cm/sec
1	0.1	64.8	
2	.2	70.0	+52
3	.3	75.0	+50
4	.4	78.5	+35
5	.5	79.3	+ 8
6	.6	77.7	-23
7	.7	73.8	-39
8	.8	68.5	-53
9	.9	63.4	-51
10	1.0	59.9	-35
11	1.1	58.4	-15
12	1.2	59.8	+14
13	1.3	63.5	+37

flash no.	time, sec	position, cm	velocity, cm/sec
13	1.3	63.5	//////////
14	1.4	68.7	+52
15	1.5	73.8	+51
16	1.6	77.8	+40
17	1.7	79.9	+21
18	1.8	78.5	-14
19	1.9	75.2	-33
20	2.0	70.0	-52
21	2.1	64.5	-55

Measured period: 1.233 sec/cycle.
$T = 2\pi\sqrt{m/k}$ = 1.11 sec.
Discrepancy due to spring mass.

Exp. C-4

3. Large glider: 395 g
   Small glider: 190 g
   Density of chain per unit length: 1.161 g/cm.

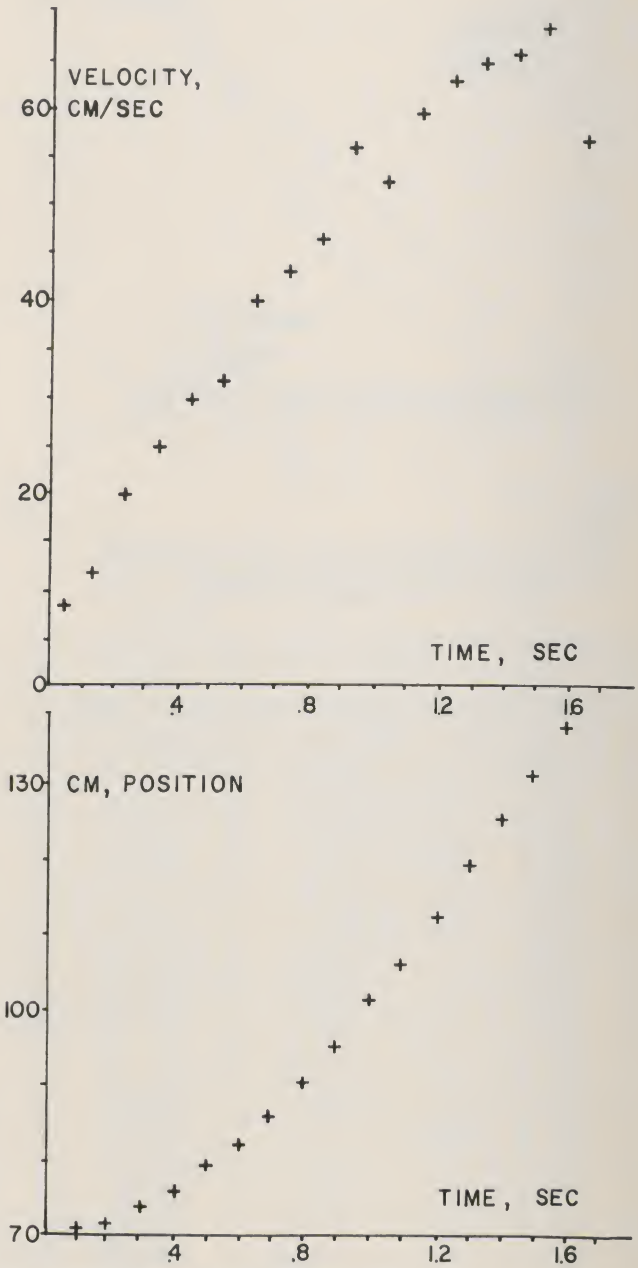
3,4,5.

mass glider (g)	distance traveled (cm)	time (sec)
395	101	1.68
395	50.5	1.61
190	100	1.18
190	50	1.12

7. flash rate: 600 fpm.

flash no.	time, sec	distance, cm	velocity, cm/sec
1	0	70	
2	.1	70.8	8
3	.2	72	12
4	.3	74	20
5	.4	76.5	25
6	.5	79.5	30
7	.6	82.7	32
8	.7	86.7	40
9	.8	91.0	43
10	.9	95.7	47
11	1.0	101.3	56
12	1.1	106.6	53
13	1.2	112.5	59
14	1.3	118.8	63
15	1.4	125.3	65
16	1.5	131.9	66
17	1.6	138.7	68
18	1.7	144.4	57

8.

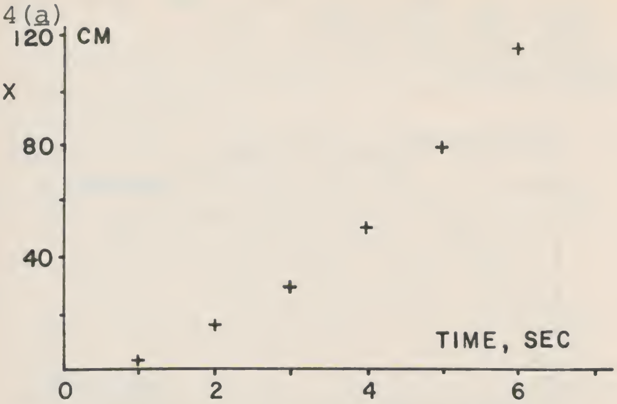


VII SOLUTIONS TO PROBLEMS

Problem 1: 1120 rpm
Problem 2: Yes, higher; 300 rpm
Problem 3: 5400 rpm
Problem 4: (a)

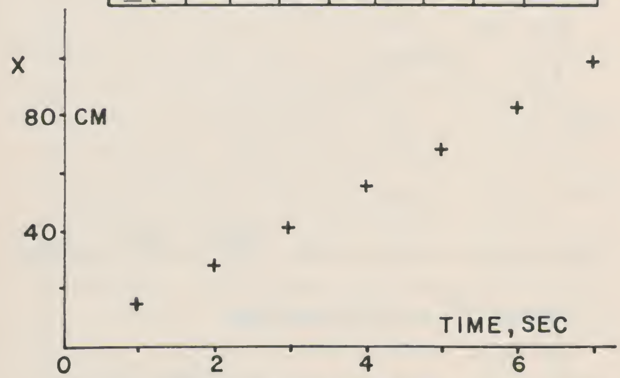
t	0	1	2	3	4	5	6
x	0	3	15	29	51	80	115

4(a)



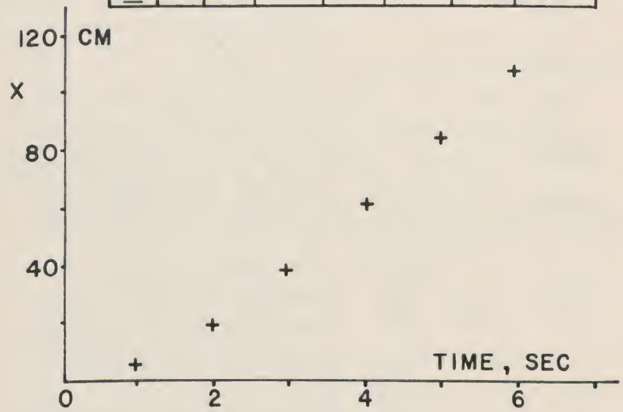
(b)

t	0	1	2	3	4	5	6	7	8
x	0	15	27	41	55	68	82	97	110



(c)

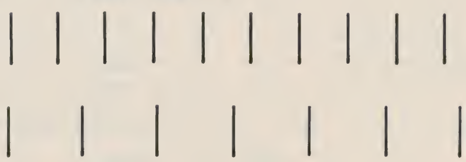
t	0	1	2	3	4	5	6
x	0	5	19	39	61	84	107



Problem 5: Both cars moving at constant speed, car 2 faster than car 1.

car 1 →

car 2 →



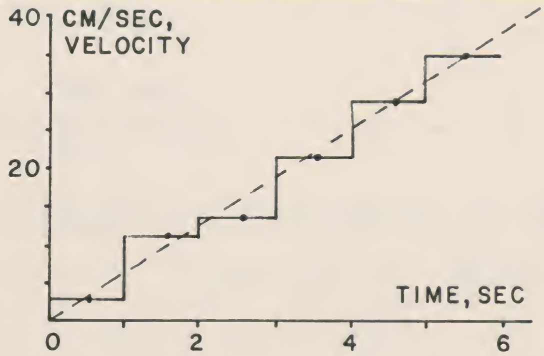
Problem 6: Both cars have the same constant speed, car 2 started from the negative side of the origin.

car 1 →

car 2 →

Problems 7 and 8: Note misprint: Prob. 7 should refer to Figure 23.

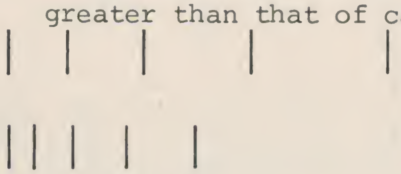
t	0	1	2	3	4	5	6 sec
x	0	3	15	29	51	80	115 cm
V_{av}	3	12	14	22	29	35	cm/sec



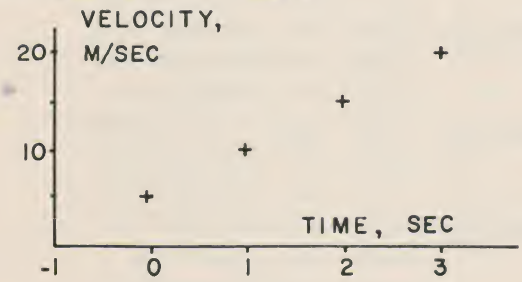
Problem 9: Both cars are uniformly accelerated, that of car 1 greater than that of car 2.

car 1 →

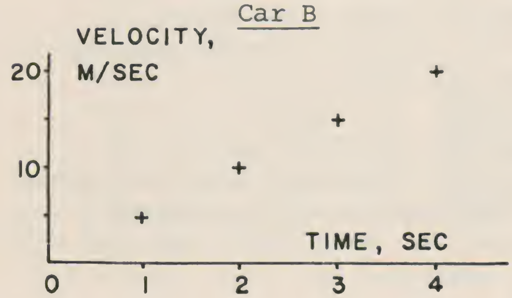
car 2 →



Problem 10: Car A



Car B

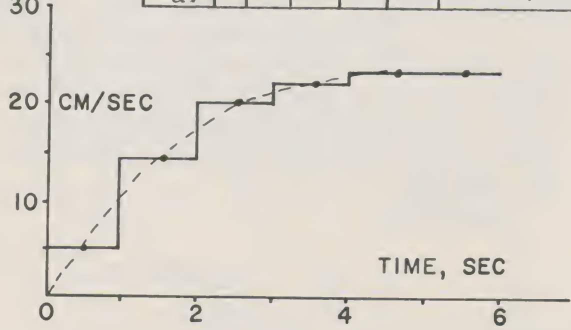


Problem 11: Constantly accelerated motion.

At time A the velocity is zero. The velocity before time A is in the negative direction, and positive after time A.

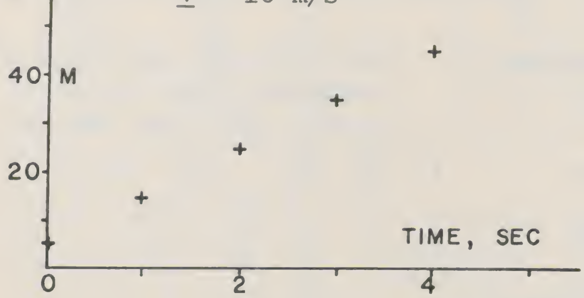
Problem 12:

t	0	1	2	3	4	5	6 sec
x	0	5	19	39	61	84	107 cm
V_{av}	5	14	20	22	23	23 cm/sec	



Yes, it matches graph c of Figure 22.

Problem 13: $x = x_o + Vt$
$x_o = 5\text{m}$
$V = 10$ m/s



Problem 14: (a) 53.3 mi/hr
(b) 48.6 mi/hr
(c) 30.7 mi/hr

Problem 15: (a) V_{av} = 35 ft/sec
(b) 70 ft/sec
(c) 350 ft/sec^2

Problem 16: (a) 110 ft/sec
(b) 59.4 sec
(c) 3.7 ft/sec^2

Problem 17: (a) .000019 sec
(b) 2.9×10^5 newtons

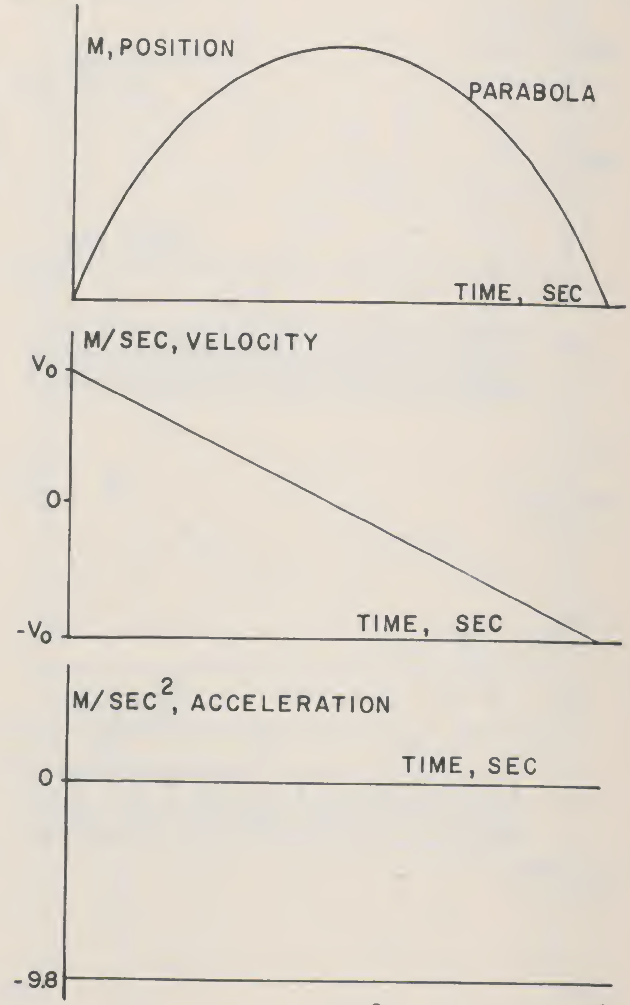
Problem 18: 282 m

Problem 19: 4.44 m/sec

Problem 20: 45.9 meters

Problem 21: The ball initially moves straight up but with a constant acceleration downward. The ball will stop momentarily at the top of its path and fall back to earth with the same acceleration.

Problem 22:



Problem 23: (a) $a = \frac{V^2}{2S} = \frac{(28\text{ m/sec})^2}{1.22\text{ m}(2)}$

$= 321.3\text{ m/sec}^2$

(b) $F = ma = 1500\text{ kg}\cdot a$
$= 4.8 \times 10^5$ newtons

(c) $\frac{V}{a} = t = .087$ sec

(d) It would be smashed.

To cause such a rapid deceleration a very large force would be required, much like the brick wall in parts a, b, and c.

Problem 24: (a) $F = ma$
$F = 700\text{ kg}\cdot 3\text{m/sec}^2$
$= 2100$ newtons

(b) $F = ma$
$F = 750\text{ kg}\cdot 3\text{m/sec}^2$
$= 2250$ newtons

($\underline{c}$) The truck has to accelerate both the car and the chain.

Problem 25: Both will decelerate at 9.8 m/sec^2.

Problem 26: ($\underline{a}$) As speed and the resistive force of the air increase, the terminal velocity is approached and the acceleration decreases.

($\underline{b}$) The force of air resistance increases with velocity until the net force on the ball is zero, and hence, the velocity stays constant at the terminal velocity.

($\underline{c}$) At the start of the motion, the ball is accelerated so the xvst curve is curved. As the speed of the ball increases, the value of the acceleration decreases (so the curvature of the $\underline{x}$ vs $\underline{t}$ curve decreases), and approaches zero as terminal velocity is approached (and $\underline{x}$ vs $\underline{t}$ becomes a straight line).

Problem 27: ($\underline{a}$) The force of air resistance decreases the net force as the person falls faster, so that terminal velocity is reached, and no more acceleration occurs. The soft ground allows a larger distance for the deceleration, and hence, smaller forces on the body.

($\underline{b}$) The parachute increases the air resistance so that the terminal velocity is much smaller.

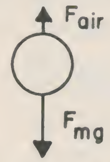
Problem 28: $\underline{a}$ & $\underline{b}$ plots should resemble those of figure 62 for one ball, and figure 42 for the other.

($\underline{c}$) No, the heavier ball has a larger mass, so that air resistance is negligible. It falls with uniform acceleration. The force of air resistance is comparable to the weight of the lighter ball, so that it approaches terminal velocity.

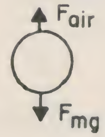
($\underline{d}$) For the heavier ball, the net force is constant, but for the lighter, the net force changes with velocity.

($\underline{e}$) Both have gravitational forces downward and frictional forces upward. The frictional force of the air increases with velocity. Lighter ball (the one that approaches terminal velocity) is foam plastic, while the heavier is metal.

For the heavier ball:



For the lighter:



VIII POST-TESTS

These are suggested sets of test questions which may be helpful to the instructor. They may be used intact, or a mix of questions may be selected. The instructor may or may not want to provide the students with some of the algebraic relations for reference during the tests.

Test 1
Section A

1. State the two rules for determining how the reference marks on a rotating object will appear when illuminated by a stroboscope: one for the case when the object makes a whole number of revolutions between flashes, and one when the flash rate of the stroboscope is a whole-number multiple of the speed of rotation.
2. Sketch a position-time graph and a velocity-time graph for ($\underline{a}$) constant-velocity motion, and ($\underline{b}$) constant-acceleration motion.
3. If your airplane flies from New York to Chicago in an elapsed time of 2 hours to cover the 800 miles, what has been the average speed of your plane? Is this the cruising speed of the plane? Why?

4. You own a sports car with a speedometer calibrated in km/hr. A friend takes the following readings as a function of time:

time (sec)	speed (km/hr)
0	0
2	18
4	36
6	54

What is the acceleration of the car in m/sec^2?

Section B

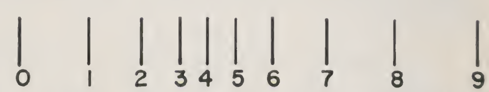
5. Sketch a graph of the motion for the following equations:
   (a) $\underline{x}$ = 50 m - 20 m/sec x $\underline{t}$
   (b) $\underline{x}$ = -40 m + 15 m/sec x $\underline{t}$
6. On a planet with $\underline{g}$ = 10 m/sec^2, a rock is dropped over an 80-m-high cliff with zero initial speed.
   (a) What is its speed after 3 seconds?
   (b) How far has it fallen in those 3 seconds?
   (c) How long will it take to hit the ground at the base of the cliff?
7. If the rock in problem 7 were thrown horizontally with a velocity $\underline{V}_{oh}$ = 6 m/sec:
   (a) What is its exact location when it has fallen for 3 seconds?
   (b) How far away from the base of the cliff will it hit? (Assume the cliff is perfectly vertical.)
8. Describe briefly but completely how projectile motion can be analyzed.

Section C

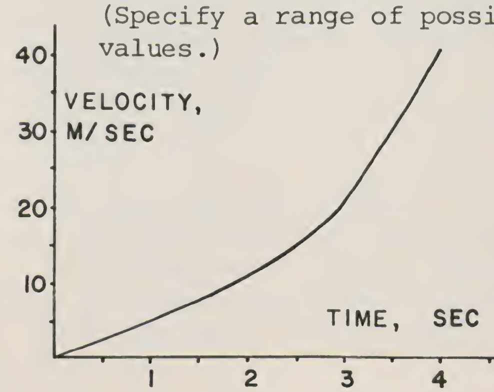
9. State Newton's three laws, and very briefly describe what they mean.
10. What force will give a 1500-kg car an acceleration of 5 m/sec^2? What body exerts this force on the car? How hard does the car push back on the body that is accelerating it?
11. Discuss what factors limit the top speed of a common imported bus which is light and box-shaped. What two things could be done to raise its top speed?
12. A weight of 500 N hung on a spring stretches it a distance of .4 m. What will be its period if it is set into oscillation? (Take $\underline{g}$ = 10 m/sec^2.)

Test 2
Section A

1. List four applications of the stroboscope. You need not describe them in detail. Explain in a brief paragraph how the stroboscope is used for <u>one</u> of the four applications.
2. A strobe photo of an air track glider is shown in the diagram.



Describe the motion of the glider, and sketch a rough $\underline{s}$ vs $\underline{t}$ plot for the glider.
3. Your small economy car has a top speed of 50 mph. If you have to take an interstate highway to a city 90 mi away, and you have 2.1 hours to get there, how long a coffee break can you take on the way?
4. From the graph, calculate the acceleration of the car between $\underline{t}$ = 0 and $\underline{t}$ = 1, and between $\underline{t}$ = 3 and $\underline{t}$ = 4. What would you expect for the magnitude of the acceleration between 1 and 3 sec? (Specify a range of possible values.)



Section B

5. You are standing at a stop light. Just as it changes and you start accelerating, a car identical to yours passes you with velocity $\underline{V}_0$ and an acceleration equal to yours. After $\underline{t}$ sec, how much faster than your car is the other car moving? After the same $\underline{t}$ seconds, how far ahead of you is the other car?
6. A photo-reconnaisance plane is catapulted from the deck of an aircraft carrier with a speed of 150 ft/sec. The launching time was 2.8 seconds. Find: (a) the acceleration of the plane, and (b) the length of the catapult.
7. A rock is tossed upward from the edge of a cliff with a speed of 30 m/sec. (Take $\underline{g}$ = 10 m/sec^2.)
   (a) At what time will it reach the highest point in its path?
   (b) How high will it rise?
   (c) With what speed will it pass the point where it was thrown? In what direction will it be moving?
   (d) What will be its position and its velocity after 10 seconds?
8. If the rock in problem 7 also were given a horizontal velocity of 9 m/sec in addition to the 30 m/sec in the vertical direction:
   (a) What horizontal distance will the rock have covered when it is at the highest point in its path?
   (b) How far away from the starting point will it be as it passes the level of the cliff on the way back down?
   (c) What horizontal distance will it have covered after 10 sec?

Section C

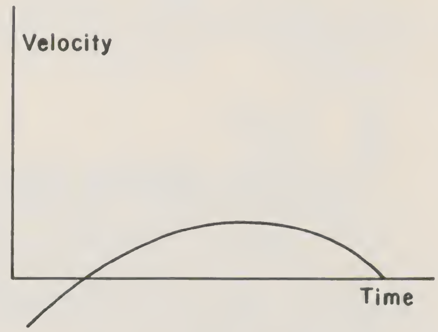
9. A car with a mass of 1200 kg has broken down and must be towed. Assume that there is no friction involved. If the only rope available has a tensile strength of 600 N (it will break if the force pulling on it is over 600 N), what is the greatest acceleration with which the car can be towed?
10. Define:
    (a) Weight
    (b) Mass
    Distinguish between them.
11. A 1000-kg car is sitting on an 11.5° grade. Calculate its acceleration if the brakes are released and it rolls without friction down the hill. What would be the acceleration of a 4000-kg truck under the same frictionless conditions? (Sin 11.5° ≃ .2; Cos 11.5° ≃ .98; Tan 11.5° ≃ .2)
12. Newton's law of gravitation says that the force with which the mass of the earth attracts an object of mass m is proportional to the mass of the object. $\underline{F}_{grav} = (\underline{K})\ \underline{m}$.
    (a) Use this fact together with Newton's Second Law to show that when an object is acted on by this force alone (i.e. it is falling freely), its acceleration does not depend on the mass of the object.
    (b) If this is the case, discuss why a rock and a feather do not both fall with the same acceleration.

Test 3
Section A

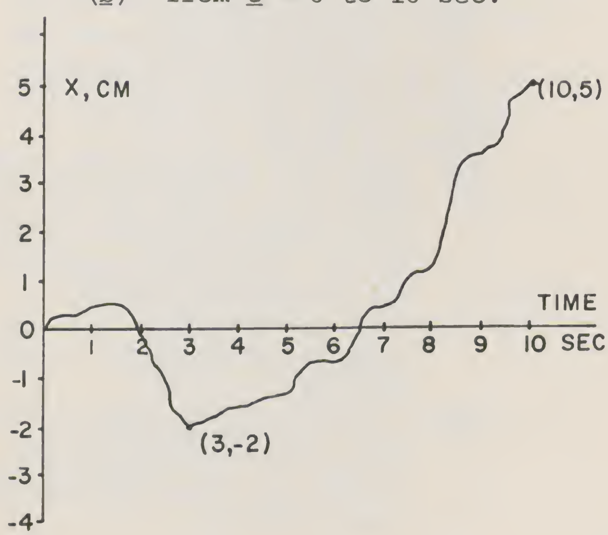
1. If you are given a disc with a single identifying mark on it that rotates at 3000 rpm (50 rps) and a stroboscope to shine on the disc, describe what an

observer will see if:
(a) the flash rate of the strobe is set at 3000 fpm.
(b) the flash rate of the strobe is set at 1000 fpm.
(c) the flash rate of the strobe is set at 6000 fpm.

2. Describe the motion represented by the graph shown.



3. The graph of the motion of a fly walking along a straight line is shown in the sketch. Calculate the average velocity of the fly:
(a) from t = 0 to 3 sec.
(b) from t = 0 to 10 sec.



4. Define the following terms:
(a) Average Velocity
(b) Instantaneous Velocity
(c) Acceleration
(d) Initial Values (for velocity, for instance)

Section B

5. A car slowing down for a red light is moving at a speed of 8 m/sec when the light changes, and the driver immediately accelerates with a = .6 m/sec^2. How far will the car travel in the next 10 seconds?
6. A quarter mile is about 400 meters. Calculate the acceleration that a car would need in order to cover this distance in 10 seconds, starting from rest.
7. A stone is dropped in a well and hits bottom in 2.2 sec. Find (a) the depth of the well and (b) the velocity with which the stone hits the water.
8. An airplane is practice bombing. If the air speed is 100 m/sec and the plane is traveling horizontally at an altitude of 500 meters, how far ahead of the target must the dummy bomb be released? (Take g = 10 m/sec^2.)

Sections B and C

9. A 1000-kg car is going up an 11.5° grade at a constant speed of 20 m/sec when it runs out of gas. Assume that there are no frictional losses.
(a) Calculate the acceleration of the car. In what direction is it accelerated?
(b) How far will the car be able to coast up the hill from the point where it ran out of gas?
(c) How long will it take the car to coast to a stop?
(d) What will be the car's acceleration as it rolls back down the hill?
(e) How will the answers be affected for a 3000-kg truck also assumed to be frictionless? (Take g = 10m/sec^2, and Sin 11.5° ≃ .2;

Cos 11.5° ≃ .98; Tan 11.5° ≃ .2.)

Section C

10. The diagram in Figure 47 shows a tugboat pulling two barges in still water. The mass of the tug is 1.5×10^4 kg; the mass of barge A is 8×10^3 kg, and that of barge B is 2×10^4 kg. The masses of ropes 1 and 2 are very, very small compared to the masses of the tug and barges. The tug is just starting to accelerate the barges, so that the drag of the water on the system is still very small. If the acceleration of the system, starting from rest is .1 m/sec^2:
    (a) Calculate the tension in rope number 1.
    (b) Calculate the tension in rope number 2.
    (c) Why do these two tensions differ?

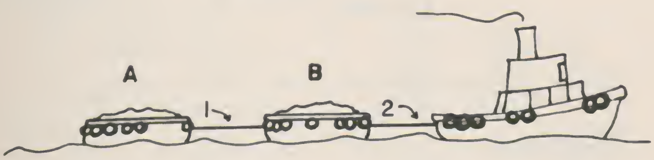
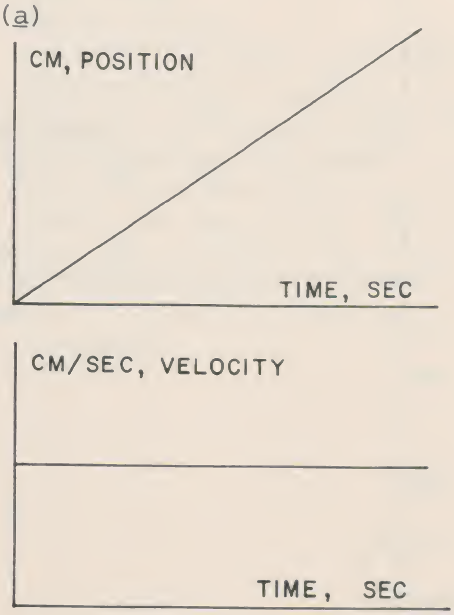


Figure 47.

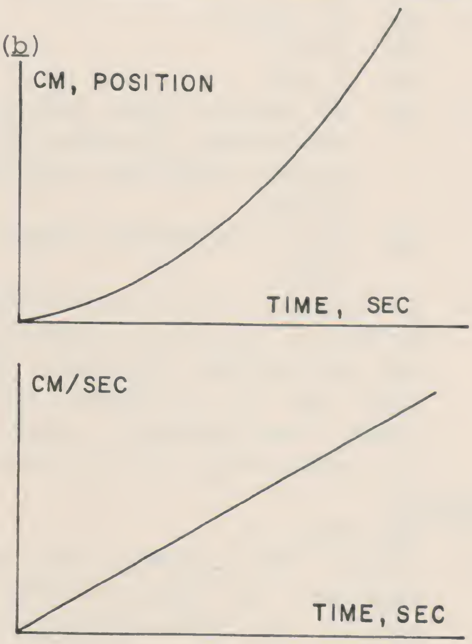
11. Why does a Continental Mark IV have to have a larger engine than an MGB in order to have a comparable acceleration? Discuss.
12. If you are given the following equation for the motion of a mass oscillating on a spring: $\underline{x} = 12 \sin (360° \frac{t}{5})$
    (a) What is the amplitude of the motion?
    (b) What is the period of the motion?
    (c) What is the frequency of the motion?

Answers to Post-Tests

Test 1
Section A
1. See page 5.
2.
(a)

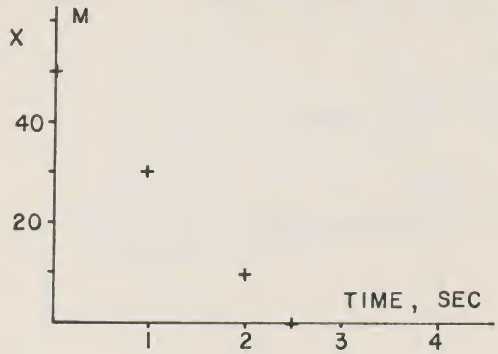


(b)

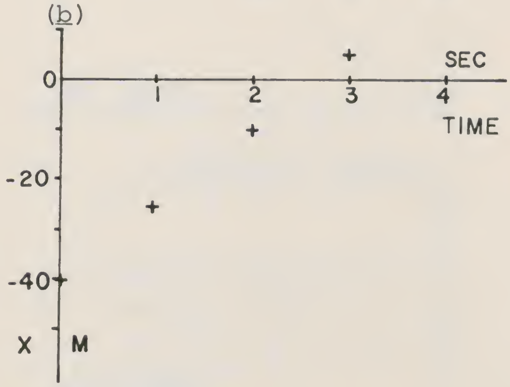


3. 400 mph; no, it is not. Time must be allowed for taxiing, attaining altitude, and waiting for landing clearance.
4. 1.5×10^2 m/sec^2

5. (a)



(b)



Section B

6. (a) 30 in/sec
   (b) 45 m
   (c) 4 sec
7. (a) 45 meters below and at a horizontal distance of 18 meters from the starting point.
   (b) 4.6 = 24 meters from cliff base.
8. The motion of the projectile can be broken up into 2 components, the horizontal (constant velocity) and the vertical (constant acceleration), since each is independent of the other.

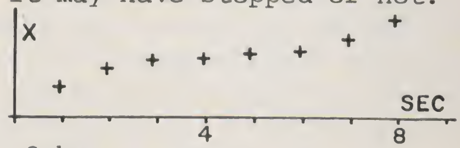
Section C

9. See page 52.
10. 7500 N; the earth or the road supplies the force, and the car pushes back with an equal force of 7500 N.
11. Air resistance, wheel friction, and low power.
    Streamline, reduce tire friction, and increase power.
12. .2 x 2π sec

Test 2

Section A

1. The stroboscope is useful as a linear speed measuring device, as a tachometer for rotational motion, for operational inspection of machinery, or many other uses.
2. The glider decelerates, then accelerates. We can't tell whether it may have stopped or not.



3. .3 hr.
4. 5 m/sec^2; 20 m/sec^2; between 5 and 20 m/sec^2.

Section B

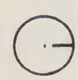
5. $\underline{V_o}$ faster; $\underline{V_o t}$ ahead.
6. (a) 53.6 ft/sec^2
   (b) 210 ft
7. (a) 3 sec
   (b) 45 m
   (c) 30 m/sec down
   (d) 200 m below start; 70 m/s downward
8. (a) 27 m
   (b) 54 m
   (c) 90 m

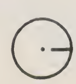
Section C

9. .5 m/sec^2
10. See page 52.
11. 2 m/s^2; same for any mass.
12. (a) $\underline{F}_{grav}$ = weight = $\underline{Km}$ = $\underline{ma}$
    $\underline{a} = \underline{K}$
    (b) Air resistance exerts negligible force on rock, but it exerts a force on the feather comparable to its weight. Without air, both would fall with the same acceleration.

Test 3

Section A

1. (a)  one steady mark

   (b)  one steady mark

(c)  two steady marks

2. Object has a negative velocity $\underline{t} = 0$. It decelerates to $\underline{V} = 0$ and accelerates in positive direction. It reaches a maximum velocity and decelerates to zero velocity.
3. (a) -2/3 m/s
   (b) .5 m/s
4. (a) See page 11.
   (b) See page 24.
   (c) See page 21.
   (d) See page 24.
5. 110 m
6. 8 m/s^2
7. (a) 24.2 m
   (b) 22 m/s
8. 1000 m. before target

Section B and C

9. (a) 2 m/s^2
   (b) 100 m uphill coast
   (c) 10 s
   (d) 2 m/s^2
   (e) independent of mass

Section C

10. (a) 800 N
    (b) 2800 N
    (c) Rope 2 is accelerating both A and B.
        Rope 1 is accelerating only boat A.
11. A larger force will be required to give a larger mass a given acceleration.
12. (a) 12 m
    (b) 5 sec
    (c) .2 Hz

IX LIST OF APPARATUS

1. Stroboscope: variable-speed flash, range 600 fpm to 3200 fpm or higher (e.g., Thornton Associates strobe model STS-300, or General Radio "Strobotac").
2. Calibrated background (e.g., pegboard with 1" hole spacing, or Thornton Associates metric grid).
3. Steel ball, painted white.
4. Plastic foam balls, 1" diameter with lead shot for weighting.
5. Self-developing camera with time-exposure capability such as that available from Thornton Associates; film.
6. Camera tripod.
7. Air track, gliders with white markers and air supply, e.g., Thornton Associates Model ATT-100 or Ealing air track.
8. Light chain about 1.5 m (optional for Exp. C-4).
9. Blow tube and hose for launching projectiles (Exp. B-2).
10. Fan or power tool for speed measurements.

CONTENTS

I INTRODUCTION

An automatic toaster is used for the study of heat, energy conservation, thermal expansion, and control. Basic electrical principles are treated, but the complications associated with alternating current are avoided.

II SPECIAL PREREQUISITES

There are no special prerequisites for this module, although the Physics of Technology Program prerequisites (high school algebra, and familiarity with the metric, English, Fahrenheit, and Celsius systems) are necessary.

III TABLE OF CONTENTS OF THE MODULE

IV GOALS

1. Clearly define in complete sentences energy, power, specific heat, heat capacity, and coefficient of linear expansion.
2. Measure the appropriate voltage and current, and calculate power, given a circuit diagram, a battery, hook-up wires, a resistor, an ammeter, and a voltmeter.
3. Measure the appropriate voltage, current, and time interval, and calculate the energy in joules, given the same equipment as for the preceding objective plus a timer.
4. Determine heat capacity, temperature change, or quantity of heat, when given 2 of these 3 quantities.
5. Given a table of conversion factors, convert these energies from one to another: joules, calories, Btu's, kilowatt-hours.
6. Determine the heat capacity of an object by measuring the temperature rise for a measured input of electrical energy using the following apparatus: the object, material to insulate the object, a voltmeter, an ammeter, a clock, a thermometer, hook-up wires, and a source of electricity.
7. Given an object made up of several different materials, determine an approximate value for the heat capacity of the object by estimating the masses of the different materials, looking up approximate values for specific heats of the materials, and performing the appropriate calculations.

8. Given a control system based on the thermal expansion of materials (such as in the toaster), describe the sequence of events by which the thermal control mechanism produces a desired result or prevents an undesirable one when energy is supplied to the device.
9. Given a process which involves the transformation of energy among several different forms and a list of energy forms, identify all forms of energy which change during the process and state which are increasing and which are decreasing during each stage of the process.
10. Given two of the following three quantities for an electric circuit, determine the third: voltage, current, power.
11. Given two of the following three quantities for a circuit, determine the third: time, power, energy.
12. An object is heated through a range in which the specific heat is constant. Given three of the following four quantities, determine the remaining quantity: heat, specific heat, mass, change in temperature.
13. An object is heated through a range in which the coefficient of thermal expansion is constant. Given three of the following four quantities, determine the remaining quantity: change in length, original length, coefficient of thermal expansion, change in temperature.
14. Given a bimetallic strip made of known metals and a table of coefficients of thermal expansion, determine which way the strip will curve when heated.
15. Given the appropriate formula, the dimensions and composition of a bimetallic strip, the coefficients of thermal expansion for both metals, and the temperature change from the situation in which the strip was straight, calculate the angle of curvature of the strip.
16. Given the appropriate formula, the dimensions and composition of a bimetallic strip, the coefficients of thermal expansion for both metals, and the temperature change, calculate the amount of movement of one end of the strip.

V DISCUSSION OF ACTIVITIES

The suggested laboratory experiments are:

1. Measure current and voltage for an immersion heater, compute power, and compare with the rated power.
2. Same as (1) but for the toaster.
3. Determine the electrical energy required to heat a cup of water. Express energy in joules and calories. Compare with energy computation based on specific heat of water.
4. Determine the heat capacity of the toaster, and compare with a rough calculation based on the mass and specific heat of the different materials in the toaster.
5. Compare the observed curving of a bimetallic strip with that predicted by the derived expression.
6. Study the toaster control system.

Because of variations in laboratory scheduling, we tried to select laboratory exercises which would provide for considerable versatility in terms of time requirements. These estimates may serve as rough guides.

Experiment	1	30 min.
	2	20 min. (assuming experiment 1 was not omitted.)
	3	50 min.
	4	90 min.
	5	60 min.
	6	90 min.

Total: 340 min. = 5 hours 40 min.

Moreover, exercises 3 and 5 can be done as demonstrations by placing the apparatus on an overhead projector.

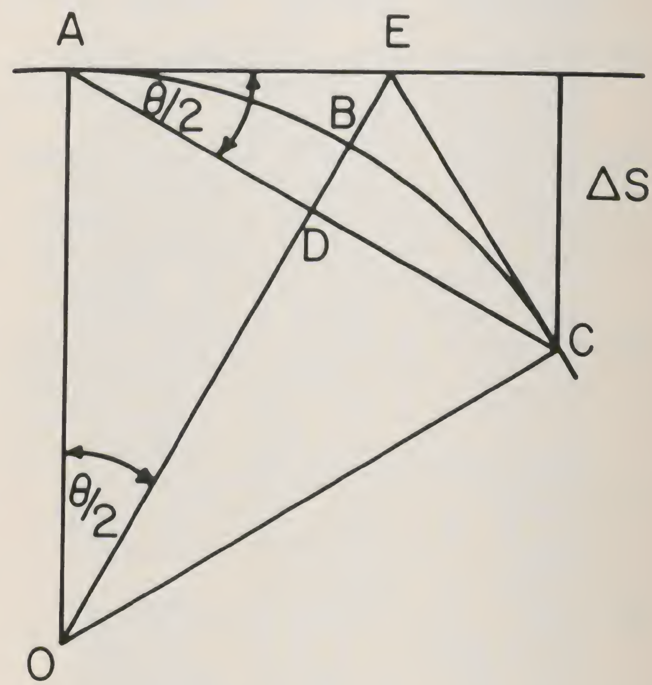
In this module you will find many places which call for more comment than is included in the student text. In many cases, the omissions are deliberate.

You will note that the laboratory instructions contain nothing on meter-reading technique. We feel that written material is not an adequate substitute for individual attention on that point. You may also note that even though the textual material alludes to the role played by the wheel in the pop-up mechanism, it is ignored in the laboratory instructions except for a question at the end. This is deliberate. The student should discover it for himself.

It was difficult to resist the temptation to include a quantitative description of kinetic energy. Such a treatment would fit in well with the discussion on energy, but kinetic energy does not play an important role in the operation of the toaster. There are other cases where the decision is more difficult. For example, one can discuss the energy transfer in the toaster without using Ohm's law, and yet Ohm's law can be introduced in a very natural way. In such situations we chose to be brief rather than complete, assuming that the instructor will supplement the text material if he finds the omissions intolerable.

Some cases where you may wish to supplement the text or refer to knowledge your students have already acquired include:

1. Quantitative treatments of gravitational potential energy, elastic potential energy, and kinetic energy.
2. More formal treatments of electricity, including Ohm's law, and the "proper" definitions of units.
3. Volume coefficient of thermal expansion.
4. Latent heat of condensation and vaporization.
5. Introduction of horsepower as another unit for power.
6. Use of radians instead of degrees in discussion of curvature of a bimetallic strip.
7. Energy as a limited resource, and the environmental effects associated with the production and use of energy (see, for example, Scientific American, September 1971, Bulletin of the Atomic Scientists, September, October, and November 1971, and American Journal of Physics, June 1972, page 805).
8. Derivation of the equations for the end movement of a bimetallic strip (pages 21 and 22). Terse versions of these derivations are given below.



ABC represents the curved bimetallic strip. The travel of the free end is represented by ΔS. Since triangles EAD and AOE are similar, angle EAD = angle AOE. Each is equal to $1/2\ \theta$.

$$\Delta S = \overline{AC} \sin (1/2)\theta$$

$= 2\underline{\overline{AD}} \sin (1/2)\theta$

$\underline{\overline{AD}} = \underline{R} \sin (1/2)\theta$

$\Delta \underline{S} = 2\underline{R} \sin^2 (1/2)\theta$

But $\underline{R} = \underline{L}_o/\theta$, where $\underline{L}_o$ is the length of the strip, $\underline{ABC}$, and θ is in radians.

$\underline{S} = (2\underline{L}_o/\theta) \sin^2 (1/2)\theta$

The expression for θ is derived in the text:

$\theta = (\underline{L}_o/d) (\alpha_b - \alpha_i) \Delta \underline{T}$ (θ in radians)

The approximate expression is obtained by utilizing the small angle approximation for θ:

$\Delta S = (2\underline{L}_o/\theta) (1/2\ \theta)^2 = (1/2)\underline{L}_o$

$\Delta \underline{S} = (\underline{L}_o^{\ 2}/2\underline{d}) (\alpha_{\underline{b}} - \alpha_{\underline{i}}) \Delta \underline{T}$

Some comments on taking the toaster apart are in order. Though the students probably can manage, it is best if you do it for them. It requires some manual skill, especially when disconnecting the wire to the solenoid. For this operation, the heater element should be braced from the inside with a screw driver to prevent excessive movement.

On the following pages you will find circuit diagrams that exhibit the power supply and the toaster connections for low voltage operation. Sample data for the laboratory exercises is also provided.

Note in particular the data on the curving of the bimetallic strip. The agreement between the experiment and the theory (using the accepted values for the coefficients of linear expansion) is very poor. If one questions the value for α for the low-expansion material and used the data to determine it, the value obtained is about 5×10^{-6} per centigrade degree.

Invar is an iron-nickel alloy with 36% nickel. Its unusually low value for α is due to a coincidence. The material undergoes a phase transition over a wide temperature change, with the high temperature phase occupying a smaller volume. This effect almost exactly cancels the normal thermal expansion. The resulting α is very dependent on the concentration of nickel:

% nickel	$\alpha(\times 10^{-6}/C°)$
30	12.0
36 (invar)	0.9
40	6.0

Thus the experimental results are consistent with the assumption that the nickel content deviates slightly from 36%.

If you feel that doing the experiment as described will be detrimental because of the "failure" effect, it can be modified to one in which the student confirms the linear response and experimentally determines the unknown coefficient of linear expansion.

VI SAMPLE DATA

Experiment 1. Electrical Power--Immersion Heater

$\underline{I} = 2.50$ amperes
$\underline{V} = 117.5$ volts
Therefore $\underline{P} = 294$ watts
(It is rated at 250 watts.)

Experiment 2. Electrical Power--Toaster

$\underline{I} = 7.30$ amperes
$\underline{V} = 116$ volts
Therefore $\underline{P} = 864$ watts
(It is rated at 900 watts.)

Experiment 3. Conversion of Electrical Energy to Thermal Energy

Volume of water = 135 cm^3
Mass of water = 135 grams
Heating time = 120 seconds
Power = 294 watts
$\underline{T} = 86.0 - 25.0 = 61.0°C$
$\underline{Q} = 8,250$ calories
Electrical energy = 35,300 joules
= 8,450 calories

These data imply a loss to surroundings of about 2-1/2%.

Experiment 4. Heat Capacity

Time (minutes)	Temperature (°C)	
0	27	(Heater on for
1	34	60 seconds)
2	44.5	
3	51	
4	56	
5	59	
6	61	
7	62	
8	62	
9	62	
10	61.5	
11	61	
12	60	
13	59	
14	58	
15	57	
16	56	
17	55	
18	54	
19	(missed)	
20	52.5	
21	51.5	
22	51	
......	....	
42	40	

Toaster was on for 60 seconds at 846 watts. Therefore,

Electrical energy = 50,800 joules
= 12,100 calories

During the period from t = 12 to t = 42 minutes, the temperature dropped 20°C. Therefore, the "rate of temperature loss" is about 0.7°C/minute. So during the 8-minute period while the temperature was rising, about 6° were "lost." Therefore, we will use for the temperature change 41°C. Thus K = 295 calories/°C.

Mass of Bakelite: 290 grams
steel case: 505 "
remainder: 520 "

Using these masses, and the suggested values for specific heat, the calculated value for the heat capacity is 273 calories /°C. This is within 8% of the experimental value.

Experiment 5. The Bimetallic Strip

S(cm)	T(°C)
1.3	16.0
1.5	16.2
2.1	19.0
2.15	19.0
3.2	24.0
4.05	28.0
4.95	32.0
4.85	31.8
5.6	35.0
5.5	34.5
7.3	42.0
8.2	46.0
7.2	41.5
6.8	40.0
6.3	38.0
5.6	35.0
4.4	29.5
3.5	25.5

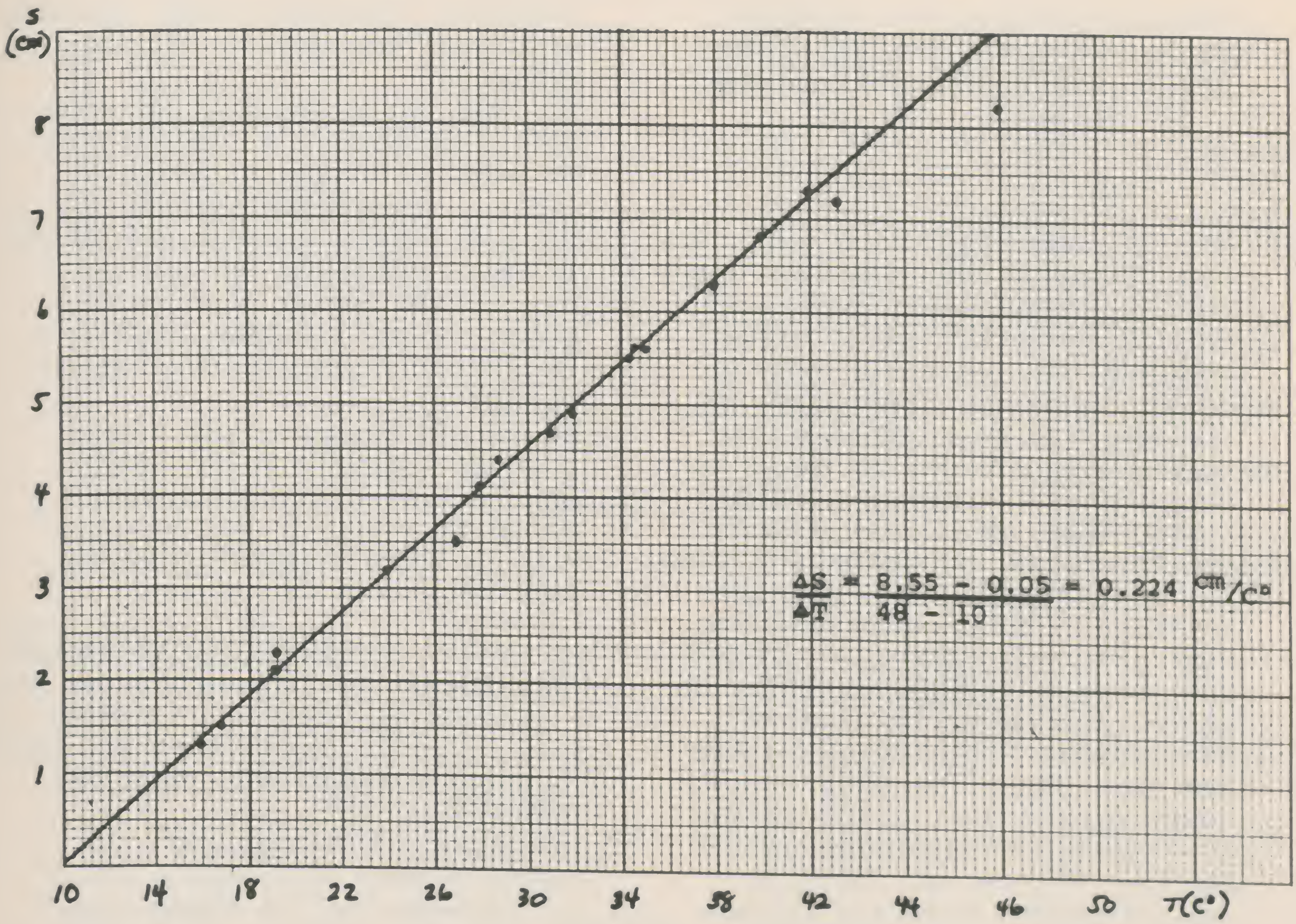
$2d$ = 0.0236 centimeters
L = 20.0 centimeters

From the graph on the next page, $\Delta S/\Delta T$ = 0.224 cm/°C. The calculated value from the equation is 0.308 cm/°C.

If we use the data to calculate a value for the difference in coefficients, the value obtained is $\Delta\alpha$ = 13.2 x 10-6 /C°. This implies a value of about 5 x 10^{-6}/C° for the low-expansion material.

VII SOLUTIONS TO PROBLEMS

1. 15 watts
2. 12 volts
3. 0.23 hours or 14 minutes
4. 67,800 calories
   270 Btu
   2.84 x 10^5 joules
   7.88 x 10^{-2} kilowatt-hours
5. 200 calories/°C
6. 136°F
7. 0.12°C/sec
8. 4,060 calories/°C
9. 0.254 feet, or about 3 inches
10. The material is iron.



11. During the drawing the chemical energy stored in the archer's body is decreasing and the elastic potential energy of the bow is increasing. During the next stage, while the arrow is being accelerated by the bow, the elastic potential energy of the bow is decreasing and the kinetic energy of the arrow is increasing. Also, there is some kinetic energy appearing in the bow, the amount being quite small in a well-designed bow.

During the rising part of the flight, the gravitational potential energy of the arrow is increasing while the kinetic energy is decreasing. There is some increase in thermal energy due to air resistance.

During the falling part, the gravitational potential energy is decreasing. The kinetic energy of the arrow increases as it falls. (However, it may reach a terminal velocity; if so, from then on the kinetic energy is constant.) Thermal energy increases due to air resistance.

When the arrow hits the ground, its kinetic energy rather abruptly decreases to zero. Most of this energy appears in form of increased thermal energy; the temperature of the arrow and the dirt around it increases slightly.

(The above discussion ignores several small effects such as the

changing gravitational potential energy during the draw and firing, and the rotational kinetic energy of the arrow.)

12. (a)); (b)).
13. 2.3°
14. 1.3×10^{-2} inch
15. When the room temperature drops, the room thermostat will close the circuit to the oil pump. (The high-expansion material must be on the bottom of the bimetallic strip to accomplish this.) Immediately the oil pump will start pumping, and current will flow in the heater for the safety-reset circuit. After a short time, if the stack control has not closed, the bimetallic strip in the safety-reset circuit will latch open, thus shutting off the pump. (The high-expansion material must be on the bottom of this strip also.) If the fuel ignites, the heat going up the stack will cause the stack control to close, thereby shorting the heater in the safety-reset circuit, and the pump will continue to pump fuel until the room thermostat opens the circuit. (The high-expansion material in the stack-control bimetallic strip must also be on the bottom.)
16. b, c, e, and h

VIII POST-TESTS

Each of the two sample examinations touches on all the objectives of the module except those involving laboratory skills. It is recommended that about 1-1/2 hours be allowed for the exam if all questions are retained. If less time is available, some of the questions should be deleted. Note also that tables of specific heat and of coefficients of thermal expansion are needed.

Examination A

1. Define the following: (a) energy; (b) power; (c) specific heat; (d) heat capacity; (e) coefficient of linear expansion.
2. A coffee pot is rated at 840 watts and is operated on a 120-volt line. It takes 10 minutes to make the coffee. (a) How much current is drawn by the pot? (b) How much energy is required to make the coffee? Express your answer in kilowatt-hours, joules, calories, and Btu's. (A table of conversion factors will be provided.)
3. An iron frying pan weighs 6 lbs. Its temperature is to be raised from 70°F to 430°F. (a) How much energy is required? (b) How long will it take, if energy is being supplied at the rate of one kilowatt?
4. An object is made up of 2 kilograms of aluminum, 3 kilograms of iron, and 1 kilogram of copper. (a) Determine its heat capacity. (b) Determine the number of calories required to raise the temperature 10°C.
5. A wire originally 50 meters in length changes in length by 2.5 centimeters when its temperature is changed by 50°C. Determine the coefficient of linear expansion.
6. A car is initially at rest at the bottom of a hill. It accelerates smoothly up the hill to 20 mph. After reaching the top, the brakes are applied enough to keep the car moving at a constant speed of 20 mph going down the hill. Discuss the forms of energy involved and state which are decreasing during each of the two stages of the trip.
7. Decide which way each of the bimetallic strips shown will curve when heated. Indicate your answer by) or (.

(a) Brass  Aluminum

(b) Copper  Iron

8. A bimetallic strip 3 centimeters long consists of brass and invar, each 0.01 centimeter thick. Determine the movement of the free end when the temperature changes by six centigrade degrees.
9. The heating system shown on the next page is designed so that only heater A operates in moderately cold weather, and both A and B operate in very cold weather. Note that one bimetallic strip is located inside the house and the other is outside. Describe how the control system produces the desired effect. Assuming that the bimetallic strips are made of brass and invar, state which material will be on top for each of the two strips.

Examination A Answers

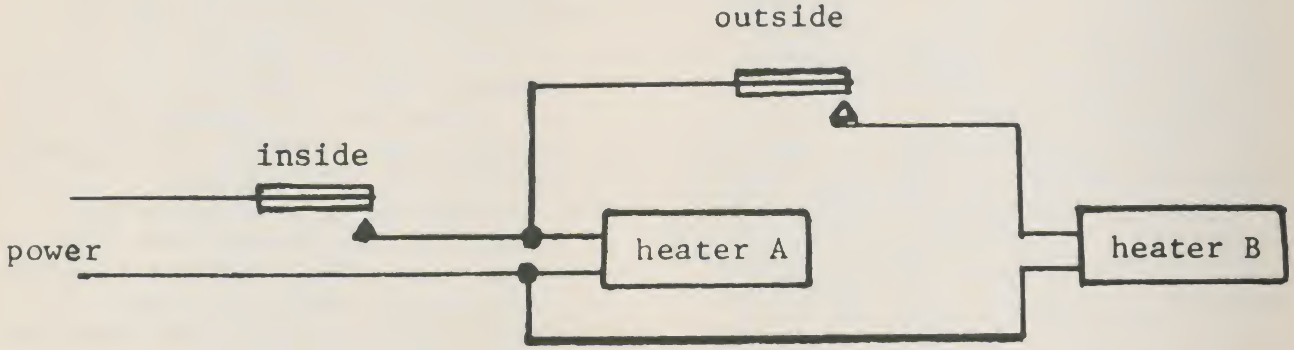
1. (The statements are taken from the text. We do not claim that they are the only acceptable answers.) (a) Energy is the capacity to do work. (b) Power is the rate of doing work. (c) $c = Q/m\Delta T$ where c is the specific heat of the material, m is the mass of the material, ΔT is the change in temperature, and Q is the heat required to produce the temperature change. (d) The heat capacity for an object is the ratio of the heat required to produce some temperature change divided by that temperature change. (e) $\alpha = \Delta L/L_o \Delta T$, where α is the coefficient of linear expansion, L_o is the original length, ΔT is the change in temperature, and ΔL is the change in length due to the temperature change.
2. (a) I = 7 amperes; (b) W = 477 Btu.
3. (a) Q = 244 Btu; (b) t = 4.3 minutes.
4. (a) K = 866 cal/°C; (b) Q = 8660 cal.
5. $\alpha \approx 10^{-5}$/°C.
6. The main forms of energy involved are chemical, thermal, kinetic, and gravitational potential. As the car goes up the hill: (a) chemical energy is decreasing as the fuel burns; (b) kinetic energy increases as the car speeds up (this includes both translational kinetic energy of the whole car and rotational kinetic energy of the wheels); (c) gravitational potential energy increases because the car is moving higher; (d) thermal energy is increasing; it appears as engine heat, exhaust, and smaller amounts due to friction.

   As the car goes down the hill: (a) unless the driver shuts the engine off, there will be a slight decrease in chemical energy; (b) Kinetic energy will be constant because the speed is constant; (c) gravitational potential energy decreases because the car is moving to a lower height; (d) thermal energy is increasing, mainly because of heating in the brakes.
7. (a)); (b) (.
8. ΔS = 1/2 millimeter.
9. As the temperature in the room decreases, the inside thermostat must curve down. This means that the invar is on top. When the temperature reaches the point for which the thermostat is set, the contacts will close. This will supply power to heater A, and also to heater B if the outside thermostat is also closed. The heater (or heaters) will raise the temperature until the inside thermostat opens.

   For the outside control to serve its purpose, it must stay open until the temperature drops to the predetermined level. Therefore the top material in the bimetallic strip must be invar. Thus if the temperature is below the predetermined level, the contacts will be closed and heater B will be activated when the inside thermostat calls for heat. Otherwise heater B will remain off.

Examination B

1. Define the following: (a) energy; (b) power; (c) specific heat; (d) heat capacity; (e) coefficient of linear expansion.



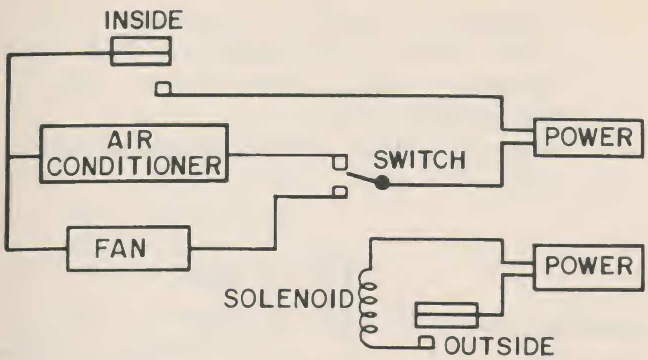
2. A 240-watt immersion heater is operated by a 12-volt car battery. (a) How much current is drawn by the heater? (b) How long will it take to heat 250 grams of water from 10°C to 90°C?
3. An object is made of two kilograms of iron, half a kilogram of Bakelite, and one kilogram of glass. (a) Determine the heat capacity of the object. (b) Determine the energy required to raise the temperature 30°C. Express the result in calories, kilowatt-hours, joules, and Btu's.
4. Determine the temperature change needed to cause a change in length of 5 centimeters in a 100-meter copper wire.
5. Decide which way each of the bimetallic strips will curve when cooled. Indicate your answer by) or (.

(a) Iron  Brass

(b) Copper  Aluminum

6. A bimetallic strip 5 centimeters long consists of iron and invar, each 0.02 centimeters thick. The strip is straight when the temperature is 10°C. Determine the amount of curving at 110°C by specifying the angle θ.

7. A man uses a windlass to lift an object. When the object is almost all the way up, the man's hand slips off the handle and the object falls to the ground. Discuss the forms of energy involved and state which are increasing and which are decreasing during each stage of the operation.
8. The system shown on the next page is designed to keep the inside of a house cool. If it is too warm inside, one of two devices is turned on: either the air conditioner or a



fan which blows in air from outside. The choice is determined by the temperature of the outside air; if it is hot, the air conditioner is used, and if it is cold, the fan is used. Describe how the control system produces the desired effect. State whether the low-expansion material will be on top or the bottom of each strip.

Note: The switch makes contact with the air conditioner side of the circuit when the solenoid is off. It is held down in contact with the fan side of the circuit when the solenoid is activated.

Examination B Answers

1. Same as Examination A.
2. (a) 20 amperes; (b) 6.4 minutes.
2. (a) 700 calories/°C; (b) 2,100 cal, 2.44×10^{-3} kWh, 8,800 joules, 8.35 Btu.
4. 29.4 C°
5. (a) (;   (b) (.
6. 16°
7. Starting from rest, the object will be accelerated upward. During this period of acceleration, chemical energy (stored in the man) is decreasing, while gravitational potential energy, translational kinetic energy of the object, and rotational kinetic energy of the windlass are increasing.

   While the object is being raised at constant speed, chemical energy is decreasing and gravitational potential energy is increasing. When the hand slips off the handle there will be a brief period during which the object continues to rise. During this period the translational kinetic energy of the object and the rotational kinetic energy of the windlass are decreasing, and the gravitational potential energy of the object is increasing.

   During the fall the gravitational potential energy is decreasing and the kinetic energy (translational and rotational) is increasing.

   During the very brief time of collision with the ground, the kinetic energy of the object decreases to zero, while thermal energy and energies of deformation increase. The kinetic energy of the windlass will be dissipated, largely in the form of thermal energy.

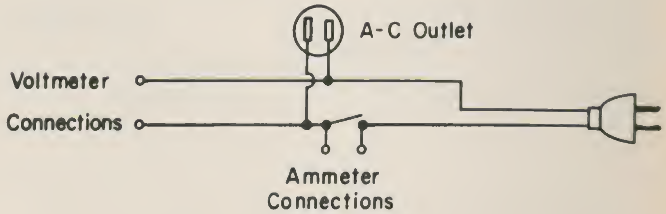
   It should also be noted that the transformation of chemical energy to mechanical energy is far from 100% efficient; much of the chemical energy is transformed to heat.
8. The solenoid should be activated when the outside temperature is low, so that the fan instead of the air conditioner will be used. Thus the outside bimetallic strip should have the low-expansion material on the top.

   To provide cooling, the strip inside the house should close the circuit when the temperature goes up. Thus this bimetallic strip should have the low-expansion material on the bottom.

   With the strips so arranged, the desired effect is produced. If it is warm inside, power will be provided to one of the two devices, depending on the position of the switch. If the temperature outside is low, the solenoid will be activated, thus holding the switch down and providing power to the fan. Otherwise the switch will be in the up position, resulting in the air conditioner being the device called upon.

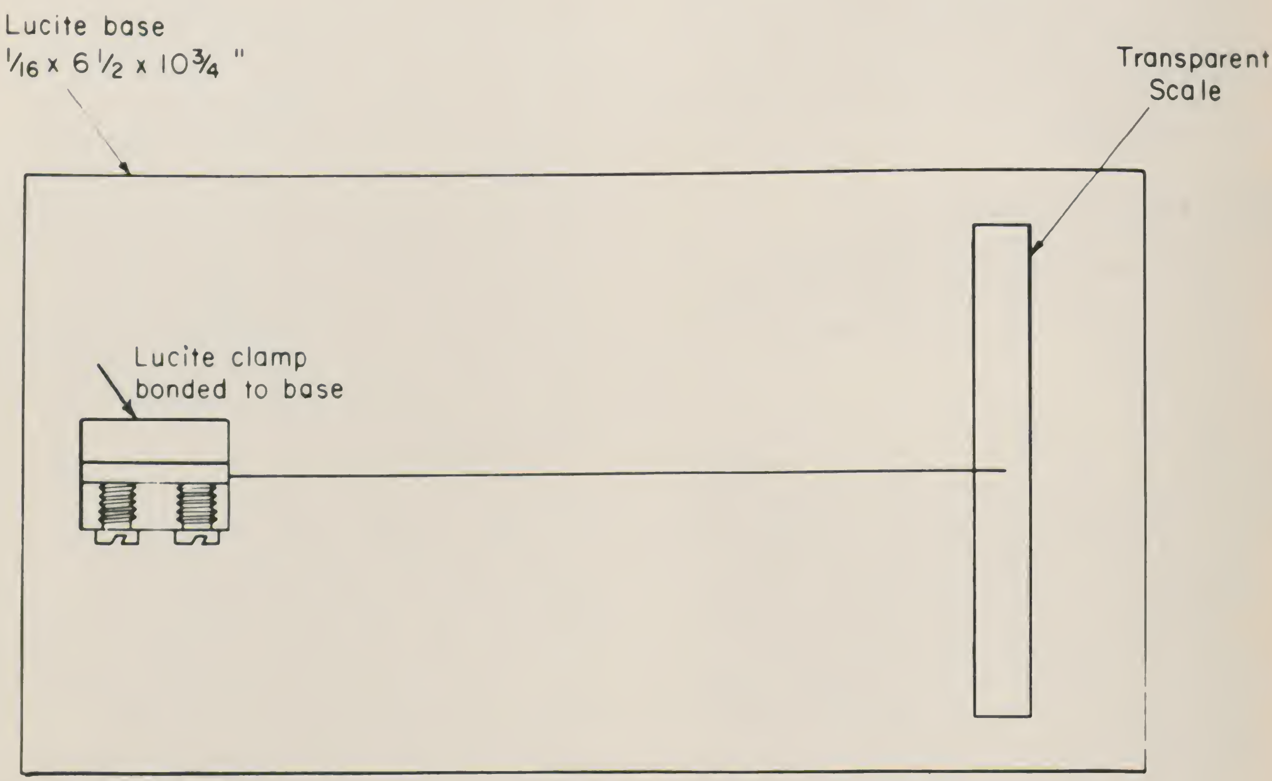
IX LIST OF APPARATUS

1. Immersion heater. Approximately 250 watts. Can be purchased in department stores.
2. Styrofoam coffee cup.
3. AC voltmeter. 0 to 120 volts.
4. AC ammeter. 0 to 10 amperes.
5. Toaster. General Electric Model T86
6. Thermometer. 0 to 100°C.
7. Dymo Aluminum Tape (for attaching thermometer to toaster). Available from supplies for Dymo tapewriters. 358-00
8. Bimetallic strip about 10 inches long. Available from Cenco or Sargent-Welch.
9. Glass dish. About 12" x 7" x 2".
10. Micrometer.
11. Hookup wire with banana connectors. Four per station. Two with alligator clips.
12. Insulating box. Sized to fit over toaster. Construction-type half-inch insulating board. Lined with aluminum foil. Hole at one end for thermometer.
13. Mounting base for bimetallic strip.
14. Transfer box.



Transfer Box

Parts for transfer box:
(a) Chassis box. 5" x 4" x 2" high (e.g., Bud CU452).
(b) Three-conductor cord with AC



plug. 10 amperes (e.g., Dearborn 9619).

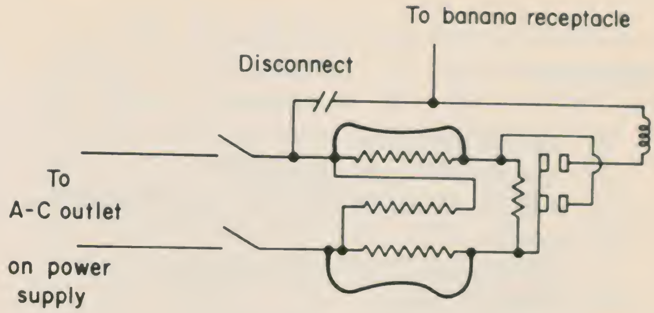
(c) Four female banana plugs, matched to available leads.

(d) SPST switch (e.g., Cutler-Hammer 7321 I-2).

(e) AC outlet.

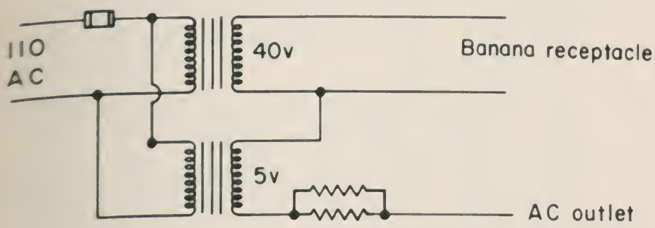
(f) Bumpers ("feet") (e.g., Smith 2194).

(g) Grommet to fit AC cord (item b above).



Toaster connections for low voltage operation

15. Low-voltage power supply.



Power Supply

Parts for power supply:

(a) Chassis box. 6" x 5" x 4" high (e.g., Bud CU2107A).

(b) Filament transformer. 6 amperes at 6.3 volts (e.g., Triad F-18X or Allied 6K 26 VF).

(c) Power transformer. 1 ampere at 40 volts (e.g., Triad F-92A or Allied 6K 104 VG).

(d) AC outlet.

(e) Female banana plug, to match available leads.

(f) Three-conductor cord with AC plug (e.g., Dearborn 9601).

(g) Resistor. Two, 1 ohm, 20 watt (e.g., Ohmite 877-8004).

(h) Resistor. 10 ohm, 2 watt.

(i) Fuse holder (e.g., Bussman HTA).

(j) Fuse, 8/10 ampere.

(k) Grommet to fit AC cord (item f above).

INSTRUCTOR'S MANUAL FOR THE TORQUE WRENCH

CONTENTS

I INTRODUCTION

The torque wrench is utilized as the basis for the study of forces and torques in equilibrium. It also provides an introductory treatment of the elastic properties of materials.

II SPECIAL PREREQUISITES

There are no special prerequisites for this module.

III TABLE OF CONTENTS OF THE MODULE

IV GOALS

This list of goals indicates what the student should be able to do after completing the study of this module.

1. Define clearly the following: torque, torque wrench, lever arm, equilibrium, static equilibrium, spring constant, cantilever beam.
2. State the conditions which the applied forces and torques must satisfy for an object to be in equilibrium.
3. Given the magnitude and direction of a force and its point of application on an object, determine the lever arm and the torque about a specified axis.
4. Solve equilibrium problems.
5. State Hooke's Law.
6. Given empirical information in either tabular or graphical form on how a system responds to an applied force, determine if it obeys Hooke's Law. If so, determine the spring constant.
7. Given the equation for the spring constant for a stretched or compressed rod, $\underline{k} = \underline{Y} \cdot \underline{A}/\underline{L}$, and the values for all but one of the physical quantities, determine the value of the unknown quantity.
8. Given the equation for the spring constant for a cantilever, $\underline{k} = (\underline{Y}/4)\ (\underline{BD}^3/\underline{L}^3)$, and the values for all but one of the quantities, determine the unknown quantity.

V DISCUSSION OF ACTIVITIES

The sequence in the student text is one which the authors feel is most effective. However, you can modify it to fit the format of your particular course. For example, if you have two class meetings before the first lab, you can cover torque and static equilibrium, then assign as homework the

predictions needed for Experiment 2. With this preliminary work, the students should have little difficulty in completing Experiments 1 and 2 in two hours. However, we urge that Experiment 1 be done earlier if possible. The "hands-on" experience with torque will reduce the abstract nature of the topic.

Experiment A-1. Torque
(Estimated time: 40 minutes)

A torque wrench is used as a "black box" to measure the torque produced when masses are suspended along a pivoted arm. The experiment is designed to show how the torque depends on the applied force, the distance from the axis to the point of application, and the angle between the radius vector and the line of action of the force.

In Question 1 of this experiment, the constant of proportionality is set equal to one, without comment. We hope the students will think about it. In any case, they are forced to do something about it in Question 2.

Experiment A-2. Equilibrium
(Estimated time: 1 1/2 hours)

A hub with arms hangs from a spring balance, and masses are suspended from the arms. Students apply the conditions for equilibrium to predict the values of "unknowns", then check the results experimentally. Six different cases are treated.

If the predictions are assigned as homework, the laboratory can be completed in less than one hour.

Experiment B-1. The Cantilever Beam
(Estimated time: 2 hours)

Students measure the deflection of a point-loaded cantilever beam. They first find that the deflection is proportional to the applied force. They then collect sufficient data to determine how the spring constant depends on the dimensions of the beam.

It was decided not to use an actual torque wrench handle in this experiment for three reasons: (1) The dependence of the spring constant on dimensions would be difficult to determine; (2) most torque wrench handles have non-uniform cross section; and, (3) point-loading is not achieved in a real torque wrench; therefore the analysis is more difficult. Nonetheless, you may wish to use a real torque wrench for the experiment, or as a demonstration. Or you may wish to calculate the scale factor for a given wrench and compare the result with the actual scale. The calculation is fairly straightforward.

$$\tau = \underline{F}\underline{L} = \underline{k}\underline{x}\underline{L}$$

$$\frac{\tau}{\underline{x}} = \underline{k}\underline{L} = (\underline{Y}/4)(\underline{B}\underline{D}^3/\underline{L}^3)\underline{L} = \underline{Y}\underline{B}\underline{D}^3/4\underline{L}^2$$

The result can be compared with the number of N·m per meter of scale length.

More information on cantilever beams can be found in a variety of engineering texts. One good reference is "Measurement Engineering, vol. I, Basic Principles", by Peter K. Stein.

VI SAMPLE DATA

Experiment A-1. Torque

A. Changing the Mass

Mass (g)	Torque (in·lb)
100	3
200	6
50	1.5

B. Changing the Position

Mass = 300 g	
Distance ($\underline{d}$)	Torque (in·lb)
12 inches	8
9	6
6	4
3	2

C. Changing the Angle of the Lever Arm

Lever Arm ($\underline{L}$)	Torque (in·lb)
12 inches	8
6	4
3	2
0	0

Answer to Question 1: $\tau = \underline{F}\ell$

Answer to Question 2: Yes. Any units of force-times-length, such as pound-feet or N·m.

Experiment A-2. Equilibrium

$\underline{W} = 0.175$ g

Case	$\underline{M}_1$ (kg)	$\underline{M}_2$ (kg)	$\underline{r}_1$ (m)	$\underline{r}_2$ (m)	$\underline{F}_s - \underline{W}$ (N)
A	0.20	0.40	0.30	0.15	5.9
B	0.40	0.30	0.15	0.20	6.9
C	0.60	0.40	0.16	0.24	9.80
D	0.51	0.40	0.11	0.20	8.9
E	0.025	0.025	0.14	0.20	0.49

Case	$\underline{M}_1$	$\underline{M}_2$	$\underline{r}_1$	$\underline{r}_2$
F	0.50	0.39	0.10	0.33

Experiment B-1. The Cantilever Beam

1. Beam width $\underline{B}$ = 2.5 cm, Thickness $\underline{D}$ = 0.32 cm, Length $\underline{L}$ = 40 cm

Suspended Mass (kg)	Suspended Weight (N)	No-load Position (mm)	Loaded Position (mm)	Deflection (mm)
0	0	30	30	0
0.2	1.96	30	33	3
0.4	3.92	30	36	6
0.6	5.88	30	39	9
0.8	7.84	30	42	12
1.2	11.76	30	48	18

Spring constant $\underline{k}$ = 627 N/m. Note: Applying the formula for a cantilever beam, this gives a value of 1.96×10^{11} for Young's modulus. This agrees with the "book value" for steel.

2. More Data

Length	Breadth	Depth	Spring Constant
40 cm	2.5 cm	0.32 cm	627 N/m
30	2.5	0.32	1400
40	1.28	0.32	303
40	1.28	0.48	1035
40	1.90	0.32	454
40	1.28	0.80	4390

Answers to Questions:

4a. decrease
b. increase
c. increase

Equation for spring constant:

$$\underline{k} = (2.5 \times 10^{10}\ \mathrm{N/m^2})\ \frac{BD^3}{L^3}$$

VII SOLUTIONS TO PROBLEMS

1. $\tau = \underline{F}\ \underline{r} \sin\theta$

$$\underline{r} = \frac{\tau}{\underline{F}\sin\theta} = \frac{100\ \mathrm{lb\cdot in}}{(8\ \mathrm{lb})(0.866)}$$

$$= 14.4\ \mathrm{in}$$

2. $\underline{F}_s = \underline{F}_1 + \underline{Mg}$

$$\underline{M} = \frac{\underline{F}_s - \underline{F}_1}{\underline{g}} = \frac{50\mathrm{N} - 30\mathrm{N}}{9.8\ \mathrm{m/sec^2}} = 2.04\ \mathrm{kg}$$

Taking torques about the point of support,

$$\underline{Mg}\ \underline{D} = \underline{F}_1\ (10\ \mathrm{cm})$$

$$\underline{D} = \frac{(30\ \mathrm{N})\ (10\ \mathrm{cm})}{(2.04\ \mathrm{kg})(9.8\ \mathrm{m/sec^2})} = 15\ \mathrm{cm}$$

3. Taking torques about the point of support,

$$\underline{F}_2\ (2\ \mathrm{m}) = \underline{F}_1\ (1\ \mathrm{m})\ (\sin 60^\circ)$$

$$\underline{F}_1 = \frac{(50\ \mathrm{N})\ (2\ \mathrm{m})}{(1\ \mathrm{m})\ (0.866)} = 115\ \mathrm{N}$$

4. Spring constant = 200 N/m

Displacement (m)	0	0.05	0.1	0.5	0.7
Force (N)	0	10	20	100	140

5. $\underline{F} = \frac{\underline{YA}}{\underline{L}}\ \underline{x}$

$$= \frac{(2 \times 10^{11}\mathrm{N/m^2})(2 \times 10^{-6}\mathrm{m^2})}{10\mathrm{m}}(2 \times 10^{-3}\ \mathrm{m})$$

$$= 80\ \mathrm{N}$$

6. Result depends on experimental data.

7. $\underline{Y} = \frac{4\underline{L}^2\tau}{\underline{BD}^3\underline{x}}$

$$= \frac{4(3.8\ \mathrm{in})^2(25\ \mathrm{in\cdot lb})}{0.1\ \mathrm{in}\ (0.1\ \mathrm{in})^3(0.5\ \mathrm{in})}$$

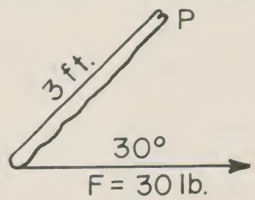
$$= 2.9 \times 10^7\ \ell\mathrm{b/in^2}$$

$$= 2.0 \times 10^{11}\ \mathrm{N/m^2}$$

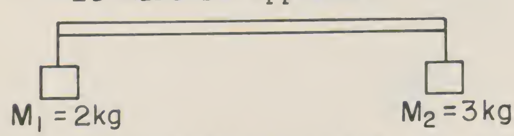
VIII POST-TESTS

Test 1.

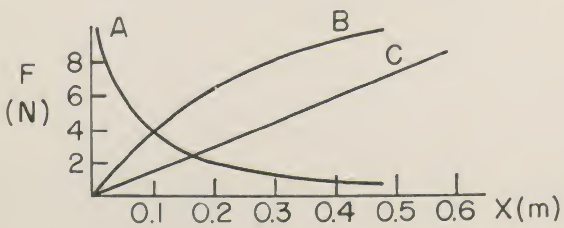
1. Define the following:
   (a) Torque Wrench
   (b) Lever Arm
   (c) Spring constant
2. State the conditions which the forces and torques must satisfy for an object to the in equilibrium.
3. Describe the behavior of systems which obey Hooke's Law.
4. For the situation shown in the diagram, determine the lever arm and the torque associated with the force F. Use the point P for the axis.



5. The meter stick shown in the figure is to be held in equilibrium by applying a single vertical force. The weight of the meter stick can be ignored.
   (a) Determine the magnitude of the required force.
   (b) Determine the point at which it must be applied.



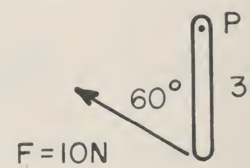
6. The graphs below show how the force depends on displacement for three different systems. Which one follows Hooke's Law? What is the value of the spring constant?



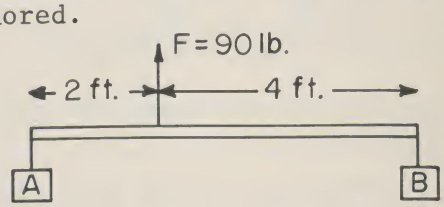
7. A brass rod with a cross-sectional area of 3 square millimeters can be stretched 5 millimeters by applying a force of 200 N. How long is the rod? (Young's modulus for brass is $9 \times 10^{10} N/m^2$.)
8. A torque wrench is made of steel, which has a value of $20 \times 10^{10} N/m^2$ for Young's modulus. The handle has a length of 30 centimeters, a breadth of 0.7 centimeters, and a depth of 0.5 centimeters. How much will the end of the handle deflect if a force of 10 N is applied to the end, at a right angle to the handle? The equation for the spring constant for a cantilever beam is:
   $\underline{k} = (\underline{Y}/4)(\underline{BD}^3/\underline{L}^3)$

Test 2.

1. Define the following:
   (a) Torque
   (b) Equilibrium
   (c) Cantilever Beam
2. Describe the behavior of systems which obey Hooke's Law.
3. State the conditions which the forces and torques must satisfy for an object to be in equilibrium.
4. For the situation shown in the diagram, determine the lever arm and the torque associated with the force F. Use the point P for the axis.



5. For the situation shown, determine the weights of objects A and B. The weight of the stick can be ignored.



6. The tables below show how the force depends on displacement for two different systems. Which one obeys Hooke's Law? What is the value of the spring constant?

(A)

Displacement (m)	Force (N)
0	0
0.01	20
0.04	40
0.08	60
0.16	80

(B)

Displacement (m)	Force (N)
0	0
0.08	2
0.16	4
0.36	9
0.64	16

7. A suspension system calls for steel rod two meters in length which will stretch no more than two millimeters if a force of 1000 N is applied. Determine the minimum cross-sectional area. (Young's modulus for steel is $20 \times 10^{10} N/m^2$.)

8. A torque wrench is to be made of brass, which has a Young's modulus of $9 \times 10^{10} N/m^2$. The handle has a length of 30 centimeters and a depth of 0.7 centimeters. How wide must it be if a deflection of five millimeters is to be produced by a 50-N force applied to the end at right angles to the handle? The spring constant for a cantilever is given by

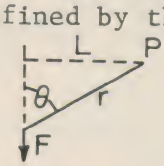
$$k = (Y/4)\ (BD^3/L^3)$$

ANSWERS TO TEST 1

1. (a) A torque wrench is a wrench whose output torque is shown by a built-in scale which is activated by the elastic flexing of the handle.
   (b) The lever arm is the perpendicular distance from the axis to the line of action of the force.
   (c) The spring constant is the constant of proportionality which appears in Hooke's Law. It is the ratio of the force to the deflection produced by that force.
2. For an object to be in equilibrium,
   (a) the resultant force must be zero, and
   (b) the resultant torque must be zero.
3. For systems which obey Hooke's Law, the force required to produce a displacement is proportional to the displacement.
4. $\ell = 1.5$ ft; $\tau = 45$ lb·ft
5. $F = 49$ N; $d = 60$ cm from the left end
6. C; $k = 13.3$ N/m
7. $L = 6.75$ m
8. $x = 6.2$ mm

ANSWERS TO TEST 2

1. (a) The torque about the point P is defined by either of the following equations. (The symbols are defined by the diagram.)



$$\tau = F\ell$$
$$\tau = F\ r \sin\theta$$

In words, the torque is the product of the force times the lever arm.
   (b) An object is in equilibrium if it is not being accelerated, even though it may be moving.
   (c) A cantilever beam is a beam which is held rigidly at one end and loaded along the length or at the other end.
2. For systems which obey Hooke's Law, the force required to produce a displacement is proportional to the displacement.

3. For an object to be in equilibrium,
   (a) the resultant force must be zero, and
   (b) the resultant torque must be zero.
4. $\ell = 2.6$ m; $\tau = 26$ Nm
5. $W_a = 60$ lb; $W_b = 30$ lb
6. B; $k = 25$ N/m
7. $A = 5 \times 10^{-6}$ $m^2 = 5$ mm^2
8. $B = 3.5$ cm

IX. LIST OF APPARATUS

Experiment A-1

25-in·lb torque wrench with ¼-inch socket
Torque arm - protractor assembly
Standard masses - 50 to 500 grams
Laboratory Stand with right-angle clamp
Plumb bob
Fish line

Experiment A-2

Spring balance - 2000 grams
Hub and arm assembly with protractor
Standard masses - 50 to 500 grams
Plumb bob
Fish line

Experiment B-1

Beam-holder assembly
Set of beams
Large C-clamp
Standard masses - 8 kg total
Fish line

CONTENTS

I INTRODUCTION

The Transformer Module is an advanced module that deals primarily with the behavior of transformers, alternating-current circuit elements, and ferromagnetic materials. Topics treated include: the transformer equation, magnetic flux, inductance, capacitance, reactance, impedance, series resonance, rms voltages and currents, AC power dissipation, voltage and current phase relationships, diamagnetic, paramagnetic, and ferromagnetic materials, magnetic circuits, reluctance, eddy currents, hysteresis, and transformer efficiency.

The module is designed to require three weeks for completion, with a substantial laboratory component that should provide the student with relatively advanced laboratory experience, particularly in the use of the oscilloscope.

II PREREQUISITES

The Transformer is an advanced module which assumes previous experience with DC circuits, magnetic fields due to electric currents, electromagnetic induction, and the concept of magnetic flux. The Multimeter and either the Automobile Ignition System or the Solenoid are assumed as prerequisites. If the Solenoid is used as a prerequisite, a treatment of Faraday's Law will be required to bridge between the modules.

III TABLE OF CONTENTS OF THE MODULE

Introduction
Prerequisites
Section A
  Transformer Characteristics
  Exp. A-1: Basic Transformer Characteristics
  AC Circuit Components
  Exp. A-2: A Simple AC Circuit
  Magnetic Circuits
  Reluctance
  Exp. A-3: Measurement of Reluctance
  Exp. A-4: Turns Ratio
  Summary
Section B
  Capacitors
  Exp. B-1: Capacitors in AC Circuits
    Part A: Capacitive Reactance
    Part B: Phase
  Inductors
  Exp. B-2: Inductors
    Part A: Inductive Reactance
    Part B: Phase
  Power Losses
  Eddy Currents
  Hysteresis
  Transformer Efficiency
  Power Factor
  Exp. B-3: Efficiency of a Transformer
  Summary
Section C
  Resonance
  Exp. C-1: Series Resonance
  Transformer Efficiency Revisited
  Summary
  Appendix: The Oscilloscope

IV LEARNING OBJECTIVES

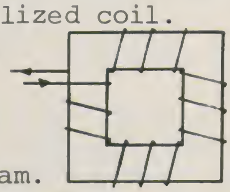
You may want to share with your students this detailed list of abilities which they should gain from the module. This list is intended to provide help to the students in identifying the significant concepts and abilities upon

which they will be tested.

The student should be able to do the following after completion of the module:

Section A

1. Draw a sketch of a transformer. Identify and label its parts, and describe the function of each and the basic operation of the transformer.
2. Describe the construction of an inductor, a capacitor, and a resistor, and describe in words how they behave in AC circuits. Discuss what voltages might be observed across each when they are connected in an AC circuit.
3. Using either an AC meter or an oscilloscope, determine both the rms and peak voltage across any specified AC circuit element.
4. Given either the rms or peak value of a voltage or a current, calculate the other.
5. Describe how the voltage across an inductance, a capacitance, and a resistance depends upon the value of each.
6. Describe the magnetic flux lines in a doughnut-shaped core wrapped with turns of wire all the way around; specify the factors which determine the amount of flux present; discuss the effect of paramagnetic, diamagnetic, and ferromagnetic core materials.
7. Describe what happens to the flux lines in a magnetic circuit when each of the following is done to a complete winding on a hollow, doughnut-shaped core:
   (a) the doughnut is filled with iron.
   (b) the winding is reduced to a single, localized coil.
   (c) the circular doughnut is converted to a square as in the diagram.



   (d) a gap is cut in the iron.
8. Define reluctance, specify what it depends upon, and describe how to measure it.
9. Write and use the equation for an ideal transformer; state what determines the ratio of secondary to primary voltage.

Section B

10. Define capacitance and capacitive reactance and state what each depends on.
11. Given an AC series circuit and an oscilloscope, determine the phase difference between any two voltages; determine the current in the circuit, and the phase difference between the current and any voltage in the circuit.
12. Indicate in words how two capacitors behave when they are connected in series or parallel in an AC circuit; calculate the effective capacitance of series and parallel capacitors.
13. Define inductance and inductive reactance and state what each depends on.
14. For series AC circuits, describe the phase relationships between $\underline{i}$, $\underline{V}_R$, and either $\underline{V}_L$ or $\underline{V}_C$; discuss reasons for the phase difference between $\underline{i}$ and $\underline{V}_L$ and between $\underline{i}$ and $\underline{V}_C$.
15. State the cause of eddy currents, describe their effect on the behavior of a transformer, and specify what can be done to minimize the effect.
16. Define hysteresis, discuss its cause, and describe its effect on the performance of a transformer.
17. Distinguish among paramagnetic, diamagnetic, and ferromagnetic materials; discuss briefly atomic behavior which could account for the observed properties of each kind of material.
18. Define efficiency of a transformer and list the effects that tend to reduce it.
19. Discuss and calculate the power dissipated in DC and AC circuits; define the power factor and describe its role in the calculation of power dissipation in an

AC circuit.

20. Given an AC voltmeter, an AC ammeter, and an oscilloscope, determine the rms voltage across, current through, phase angle, and power factor for a specified AC circuit element, and calculate the average power consumed in watts and the heat energy, in joules, generated in a given time period.
21. Describe and make measurements by which the efficiency of a transformer can be calculated, using the apparatus described in objective 20 above.

Section C

22. Define resonance and specify two different ways that resonance can be achieved in an LRC series AC circuit; state how the resonance frequency depends on the circuit elements and calculate it, given the values of the elements.
23. Given a diagram for an AC series circuit or transformer circuit, and the necessary AC sources, inductors, resistors, capacitors, meters, transformer, and wire, connect the circuit correctly without damaging any elements.
24. Discuss the production of heat in the coils of a transformer, energy dissipation associated with the changing flux in the core, and the factors governing the quality of flux linkage between coils. Describe the effects these can have on the current in the primary and the voltage across an open-circuit secondary.
25. Discuss effects that alter the values of the input and output voltage and current ratios from what they would be for an ideal transformer.
26. Describe the effect of changing the load resistance in the secondary circuit of a transformer; mention what happens to the primary and secondary currents, the secondary voltage, and the efficiency.

V DISCUSSION OF ACTIVITIES

The laboratory activities are slightly more advanced than those for some of the other POT modules. It is presumed that the students will be able to read and wire simple circuit diagrams, and will be able to perform simple measurements on the oscilloscope.

It is intended that in the study of this module, the students will spend a substantial part of their effort on the laboratory component. Many of the experiments can be performed as demonstrations, but in most cases, the students would probably derive more benefit from performance of their own laboratory work. Equipment expenses can be minimized if parts of the laboratories are staggered so that less expensive, single-trace scopes could be used for voltage measurements and a few dual-trace scopes could be rotated around the class for the phase measurements. Alternatively, with some added class material, the phase angles can be measured by analysis of Lissajous ellipses, displayed on single-trace scopes. Another approach, at intermediate cost, would be to utilize an electronic switch such as that available from the Heath Company to convert a single-trace scope to a dual-trace.

A low-voltage 60-Hz power supply is used because of its low cost. An isolation transformer, either as a component of the power supply or as a part of the external circuit, is essential for greater safety and because most scopes have a case ground. If signal generators are available, they would be preferable so that the frequency can be more easily varied (see Experiments B-1, B-2, and C-1).

Experiment A-1--Basic Transformer Characteristics (estimated time, 50-70 min.): Observation of a transformer and its component parts. Measurement of stepped up or stepped down voltage.

Several core materials are studied, including laminated iron, solid iron, aluminum, and wood. Observation of effects of removal of coil from the iron core.

Experiment A-2--A Simple AC Circuit (estimated time, 50-70 min.): Introduction to the use of oscilloscope for voltage measurement. Measurement of voltage across resistors, capacitors, and inductors. Filter chokes of a few to several henries can be used for the inductances in this module, if more expensive precision inductors are not available. However, because the inductance of filter chokes may vary with the operating current, the labeled inductance may be inaccurate by several percent.

Experiment A-3--Measurement of Reluctance (estimated time, 45-60 min.): Measurements of secondary voltage (which is proportional to the flux in the core) and thickness of paper shims inserted as a gap in the core are used to calculate the relative permeability of the solid iron transformer core by means of a plot of $1/V_2$ vs. the number of shims. As derived in the module, the plot is predicted to be a straight line. For small numbers of shims (up to 6 or 8) the plot will generally be linear. However, for a larger number of shims, $1/V_2$ may increase sublinearly. If the demountable student transformer with the solid iron core does this, it is probably because of non-linearities in the energy losses. As an illustration of this effect, see the plot of the inverse of the secondary voltage versus the number of shims which is shown on the next page. If the plot obtained with the apparatus used by your class is not linear, the accuracy of the value calculated for the relative permeability will be reduced. Nevertheless, it should give a reasonable order of magnitude value for the relative permeability.

Experiment A-4--Turns Ratio (estimated time, 50-60 min.): Plot of the primary voltage vs. the secondary voltage for a single pair of coils. Plot of secondary voltage vs. the number of turns in the secondary coil. Plot of the inverse of the number of turns in the primary coil vs. secondary voltage. The plots are used to establish the ideal transformer equation.

Experiment B-1--Capacitors in AC Circuits (estimated time, 60-80 min.): Part A establishes the proportionality of the AC current through a capacitor to the input voltage, and by varying capacitance at fixed input voltages, shows that the capacitive reactance varies as $1/C$. With the same technique, capacitors connected in series and parallel are studied. An optional step, if a signal generator is available, shows the frequency dependence of the capacitive reactance. In part B, the phase between the voltage and current is measured for a capacitor.

Experiment B-2--Inductors (estimated time, 50-70 min.): This experiment is a treatment of inductors that is almost exactly parallel to the previous experiment with capacitors. Because of the similarities, this experiment should proceed more smoothly than the previous one. Recall the comment in Exp. A-2 on the use of filter chokes as inductors.

Experiment B-3--Efficiency of a Transformer (estimated time, 60-80 min.): The input and output voltages and currents are measured for a series of pure resistance loads varying from open circuit to about 10Ω. The phase between the input current and voltage is also measured, and the transformer efficiency is calculated. Carbon resistors or light bulbs may be used for the secondary load, with the exception of the 10kΩ load, which is not easily obtainable as a bulb. The resistances of the loads will be calculable from the data, but as a rough guide in the selection of bulbs, resistances of some typical bulbs are listed with the sample data.

Experiment C-1--Resonance (estimated time, 50-70 min.): A conventional series resonance experiment.

VI SAMPLE DATA

Exp. A-1

Steps 2-8:

	Primary- 400 turns	Secondary- 200 turns
	Input V	Output V
Laminated Iron	10.0 VAC	4.6 VAC
Primary Removed	10.0 VAC	0.0 VAC
Secondary Removed	10.0 VAC	0.0 VAC
Solid Iron	10.0 VAC	2.8 VAC
Aluminum	10.0 VAC	0 VAC
Wood	10.0 VAC	0 VAC
Reverse Coils	10.0 VAC	18.2 VAC

Step 9: Hold coils one on top of other with axes aligned for maximum voltage with no core.

Exp. A-2

Step 3: 10 V_{rms}, 5.6 cm peak to peak, 28 V peak to peak (5V/cm).

Steps 4&5: .5 V_{rms} = 1.4 V peak to peak across each resistor.

~6 V_{rms} = 17.0 V peak to peak across 2-μF capacitor.

11 V_{rms} = 31.1 V peak to peak across 1-μF capacitor.

5 V_{rms} =14.1 V peak to peak across 2.5-H inductance.

5 V_{rms} = 14.1 V peak to peak across 2.5-H inductance

Step 6: 1 V_{rms} = 2.8 V peak to peak across both resistors.

Step 8: 12-volt battery deflects beam 2.4 cm, giving 5V/cm calibration factor.

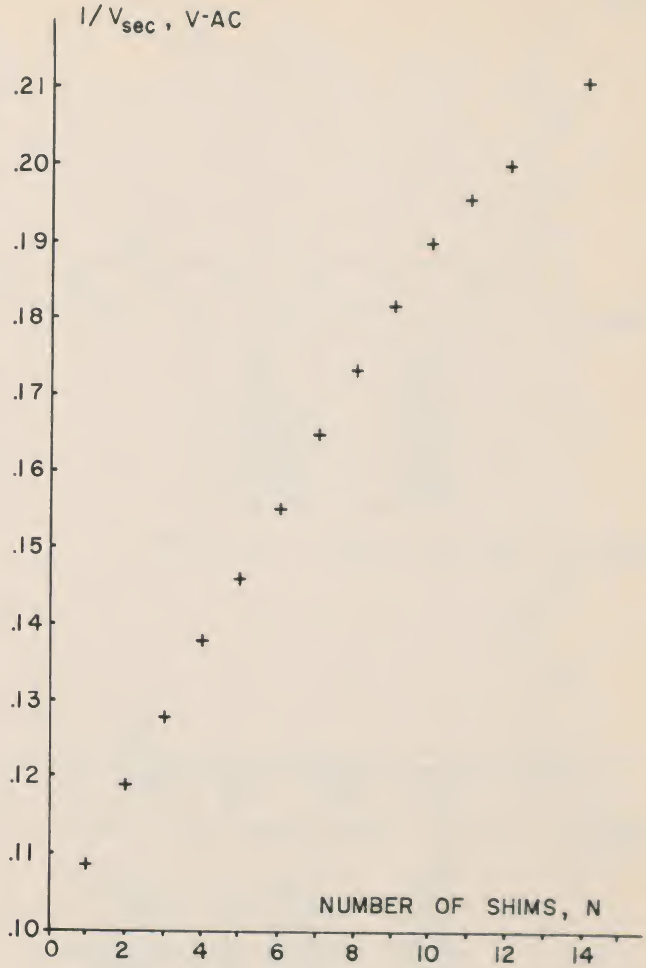
Exp. A-3

Step 1: $I_{primary}$ = 1A (no gap)

Step 2: $V_{secondary}$ = 10 V (no gap)

Steps 4&5:

n (shims)	V_2
1	9.2 V
2	8.5 V
3	7.8 V
4	7.3 V
5	6.8 V
6	6.4 V
7	6.0 V
8	5.8 V
9	5.5 V
10	5.3 V
11	5.1 V
12	5.0 V



Question 3: n = 12 shims

Question 4: 1 shim = .22 mm

12 shims = 2.64 mm

gap = 5.28 mm

Question 5: ℓ_{core} = 318 mm

$$\frac{\mu}{\mu_0} = \frac{318\ \text{mm}}{5.28\ \text{mm}} = 60$$

Exp. A-4

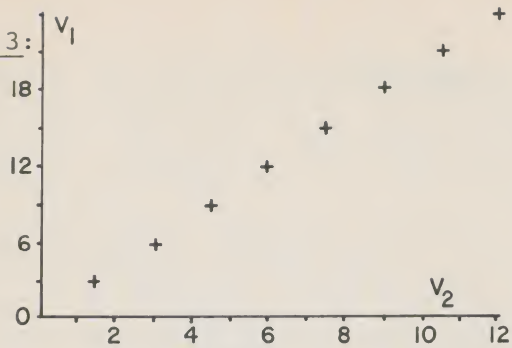
Step 1: N_1 = 400 turns

N_2 = 200 turns

Step 2:

V_1	V_2
3 V	1.51 V
6 V	3.02 V
9 V	4.51 V
12 V	6.03 V
15 V	7.52 V
18 V	9.01 V
21 V	10.52 V
24 V	12.03 V
too high for transformer	

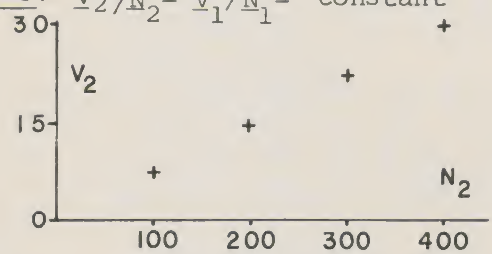
Step 3:



Step 4: N_1 = 200 turns, V_1 = 15 V

N_2	V_2
100	7.5 V
200	14.8 V
300	22.4 V
400	29.7 V

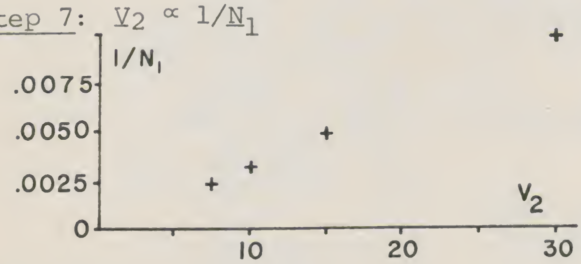
Step 5: $V_2/N_2 = V_1/N_1$ = constant



Step 6: N_2 = 200 turns, V_1 = 15 V

N_1	V_2	$1/N_1$
100	29.8 V	.01
200	14.9 V	.005
300	10.0 V	.0033
400	7.51 V	.0025

Step 7: $V_2 \propto 1/N_1$



Exp. B-1

Step 1: R = 100 Ω

Step 3: V_{input} = 10 V_{rms}, 14.1 V peak

Step 6: V_R = .6 V peak
C = 1 μF
i_{peak} = 6 mA

Step 7: An additional 100 Ω made no noticeable difference.

Step 8: V_C = 18.5 V peak; V_C larger than V_R.

Steps 9&10: V_C reduced by 2, V_R is reduced by about 1/2; I_{peak} = 3.5 mA; V_R = .35 V peak.

Step 11: V_R = 1.2 V peak, increased
C = 2 μF
i_p = 12 mA, increased

Step 12: Parallel capacitors, 1 μF and 1 μF, same as 2 μF.

Step 13: Series capacitors, 2 μF and 2 μF, same as 1 μF.

Step 14: V_{in} = 3 V_{rms}, f = 30 Hz, C = 1 μF; V_R = 60 mV peak voltage; 1 cycle = 3.5 cm on 10 msec/cm scale

Step 15: V_{in} = 3 V_{rms}, f = 90 Hz, C = 1 μF; V_R = 200 mV peak voltage; 1 cycle = 5.6 cm on 2 msec/cm scale
NOTE that these voltages must be corrected for the fact that the input voltages are different than that for the 60-Hz case before the comparison can be made.

Part B: V_C lags V_R (and also I) by 90° as closely as can be determined on the scope.

Exp. B-2

Step 1: R = 100 Ω, L = 5 H

Step 3: If the scope is capable of a high enough gain so that a V_R of less than 100 mV will be measurable, we recommend using 10 V for the input voltage, rather than the 30 V suggested in the module.

Step 4: V_{in} = 10 V_{rms} = 14.1 V_{peak} = 28.3 $V_{p\ to\ p}$
V_R = 1.35 V peak to peak
I_R = 13.5 mA peak to peak

Step 5: Second resistor causes no noticeable change.

Step 6: V_L = 8.4 V peak to peak

Step 7: V_L reduced to 4.2 V peak to peak

Step 8: V_R = 60 mV peak to peak
I_R = .6 mA peak to peak

Step 9: L = 10 H
V_R = .68 V peak to peak
I_R = 6.8 mA peak to peak
V_R and i should be proportional to L.

Step 10: V_{in} = 3 V_{rms}, f = 90 Hz, L = 5 H, R = 100 Ω; V_R =

120 mV peak; 1 cycle = 5.6 cm on 2 msec/cm scale

Step 11: V_{in} = 3 V_{rms}, f = 45 Hz, L = 5 H, R = 100 Ω; V_R = 100 Ω; V_R = 240 mV peak; 1 cycle = 4.5 cm on 5 msec/cm scale. NOTE that these voltages must be corrected for the fact that the input voltages are different than that for the 60-Hz case before the comparison can be made.

Part B V_R (and also I) lags V_L by almost 90°. Because of the resistance of the inductor, this phase angle may be measurably less than 90°.

Exp. B-3

Steps 2-6: Variable transformer setting = 10 V_{rms}
Primary turns N_1 = 400
Secondary turns N_2 = 800

load resistance R_L (bulb wattage)	open	10 kΩ	1100 Ω (7½ W)	616 Ω (15 W)	121 Ω (40 W)	45 Ω (100 W)	18.5 Ω (150 W)	10.2 Ω (200 W)
primary voltage V_1 (V)	10	10	10	10	10	10	10	10
primary current I_1 (A)	0.0345	0.036	0.057	0.082	0.282	0.5	0.62	0.652
primary phase angle ϕ	61°	58°	36°	23°	28°	40°	54°	61°
input power = $V_1 I_1 \cos\phi$ (W)	0.167	0.191	0.461	0.75	2.49	3.83	3.64	3.16
secondary voltage V_2 (V)	20.2	19.9	19.8	19.4	16.0	10.5	5.5	3.2
secondary current I_2 (A)	0.0	0.002	0.018	0.0315	0.132	0.235	0.297	0.315
output power = $V_2 I_2$ (W)	0	0.04	.36	.61	2.11	2.47	1.63	1.01
efficiency = P_{out}/P_{in} x 100	0	20%	77%	81%	85%	64%	45%	32%
V_2/V_1	2.02	1.99	1.98	1.94	1.60	1.05	.55	.32
I_1/I_2	∞	18.0	3.16	2.60	2.14	2.12	2.09	2.07

See Answers to Questions in Section VI for discussion of these results.

Exp. C-1

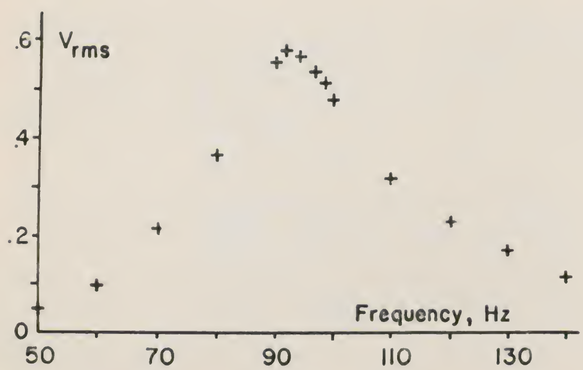
Step 2: L = 1 H, C = 3 μF, R = 100Ω;

$f = \frac{1}{2\pi\sqrt{LC}} = 92$ Hz

Steps 3&4: V_{in} = 1 V_{rms}

Freq., Hz	V_R (rms)
50	.05 V
60	.10 V
70	.22 V
80	.37 V
90	.56 V
92	.58 V
94	.57 V
96	.54 V
98	.52 V
100	.48 V
110	.32 V
120	.24 V
130	.18 V
140	.12 V

Step 5:



VII SOLUTIONS TO PROBLEMS AND ANSWERS TO QUESTIONS

Exp. A-1

1. Maximum secondary voltage is obtained without a core by placing one coil on top of the other with the axes aligned.
2. Laminated iron largest; solid iron about 40-60% of laminated core voltage; aluminum and wood, negligible secondary voltage.
3. Larger secondary voltage when the secondary has more turns.

Exp. A-2

1. Step 3 voltage is peak-to-peak value of input voltage. Variable transformer calibrated in rms. V_{rms} = .707 x $V_{p\ to\ p}/2$
2. Yes
3. Yes
4. No, voltage greatest across smaller capacitor.
5. Yes
6. No, the voltages add up to a value larger than the input voltage.

Exp. A-3

1. For a small number of shims the curve should be straight. The graph for over 8 or 10 shims may be sublinear.
2. $\mathcal{R}_T = \mathcal{R}_{Iron}$ when n = 0.

3-5. See sample data.

Problem 1: V_2 = 96,000 V

Problem 2: N_1/N_2 = .105; N_2 = (.105) x 200 = 21 turns

Question 1: (a) No; since the power frequency changes very little if at all (.05 Hz), power transformers never operate at any other frequency.
(b) This is an application where fidelity is required; hence, you want all frequencies entering the transformer to be affected the same so that the relative amplitude for voltages of different frequencies is not changed by the transformer.

Problem 3: $C = 1/2\pi f X_C = 5.3 \times 10^{-5}$F = 53 μF

Problem 4: $X_C = V_{rms}/I_{rms}$ = 40 V/.13A = 308 Ω

Exp. B-1

Question 1: V_R is 90° ahead of V_C.

Question 2: At the instant when charge is maximum, V_C is largest.

Question 3: The current is zero whenever the capacitor has a full charge.

Question 4: Zero, because the current is zero.

Question 5: Yes. (See figure 27.)

Problem 5: $X_L = 2\pi f L_p$ = 9400 Ω.

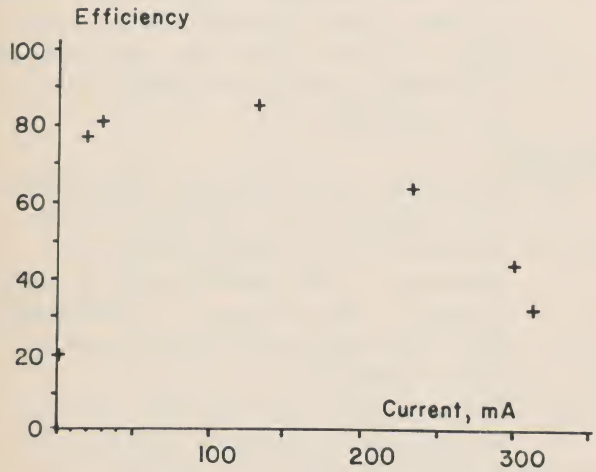
Problem 6: $\cos\phi = \frac{P}{VI}$ = .76, ϕ = 41°

Exp. B-3 See Section VI for typical sample data that might be used as the basis to answer these questions.

Question 1: A peak efficiency should

be observed. (See graph.) Other transformers may have different graphs, and the selection of loads used here may not show the decrease in efficiency at higher currents, particularly for heavier transformers.

Plot of efficiency vs. secondary current



Question 2: No current can flow in an open circuit, so when a load or current path is formed, the current can only increase.

Question 3: The primary current is smallest when the secondary is open. The primary current increases when a load is put in the secondary circuit.

Question 4: The secondary voltage decreases for smaller load resistance values.

Question 5: The voltage ratio V_2/V_1 should be very close to the turns ratio N_2/N_1.

Question 6: The larger the resistance of the secondary load, the higher the secondary voltage.

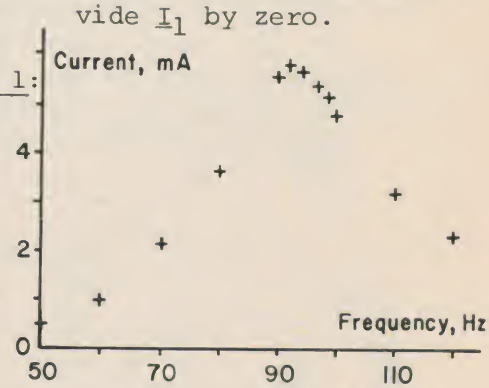
Question 7: The smaller the load resistance, the larger the primary and the secondary currents. For larger currents in the secondary, both the primary and the secondary currents change by roughly the same percentage. This is not true for smaller currents.

Question 8: The ratio of V_2/V_1 will equal N_2/N_1 only for an open secondary circuit. As the secondary current increases, this ratio decreases until it is well below the ideal transformer ratio for large currents.

Question 9: See data table, Section VI. The current ratio decreases, approaching N_2/N_1 for smaller load resistances or higher secondary currents, as the power current becomes larger than the flux current. We can't use the open secondary because I_2 is zero and we can't divide I_1 by zero.

Exp. C-1

Question 1:



Smallest voltage 50 mV, largest voltage 600 mV; smallest current .5 mA, largest current 6.0 mA. Current rises rapidly near resonance. At resonance, $X_{eff} = V/I = 1/5.7 \times 10^{-3}a = 175\ \Omega$. Effective impedance larger than R, should be approximately equal to $R + R_{dc}$ of the inductor.

Question 2: Should be close.

Problem 7: $C = 1/4\pi^2 f^2 L = 5.6 \times 10^{-11}$F $= 56$ pF

Problem 8: $f = 1/2\pi\sqrt{LC} = 71$ Hz

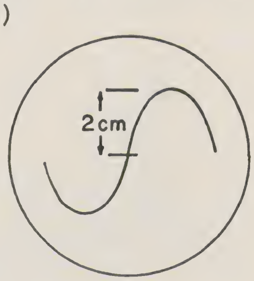
VIII POST-TESTS

The following are two sample Post-Tests to evaluate student performance on this module. Clearly, each is too long for a 50-minute exam period. Either the exam period must be lengthened or the number of questions requiring answers decreased. It is expected that about five questions would constitute an hour exam, so that several tests could be constructed from the following two tests.

<u>Test 1</u>

<u>Section A</u>

1. Draw a sketch of a simple transformer. Label the parts and describe how a transformer can be used to step voltages up or down.
2. A physics student observes the scope trace shown in the diagram, and also finds that a 1.5-volt battery deflects the trace 3 cm. What is the peak voltage of the trace shown? The rms voltage? ($\sqrt{2} \simeq 1.4$)



3. What is reluctance? How does the flux in an iron ring change if the reluctance of the ring is increased? Decreased? Describe two ways in which the reluctance of the ring can be increased.
4. An engineer is designing a transformer to step down 1200 V to 120 V. If the primary has 15,000 turns, how many will the secondary have to have? How many would it have to have in order to step the voltage up to 12,000 V?

<u>Section B</u>

5. What is capacitive reactance? Write an expression for it. Show how it can be used to find the current through a capacitor when the voltage across it is known.
6. A 60-Hz voltage of 62.8 V (rms) is applied across an inductance of .5 H. What current will flow?
7. What are eddy currents? How are they produced? What is their role in a transformer? How can their effects be minimized?
8. If the AC voltage across a circuit element is 30° out of phase with the current through it, what is the power factor? If the voltage is 100 V and the current is 3 A, what power is dissipated in the element?

<u>Section C</u>

9. How will the resonant frequency of a <u>LRC</u> series circuit be affected if the capacitance is doubled? The inductance is quadrupled? The voltage is halved? Show how you arrived at each of your answers.
10. Discuss why the current in an AC resonant circuit can be so large when the sum of the separate AC impedances of the circuit elements would appear to indicate that a much smaller current should be drawn. How much energy is being dissipated in the capacitor, the inductor, and the resistor? How is each calculated?
11. Define efficiency of a transformer. Can a transformer be more than 100% efficient? Why? Why do transformer efficiencies drop at higher power outputs? Mention two reasons.
12. Discuss the ways in which energy is dissipated in a transformer. Discuss how each can be minimized. How do increasing secondary currents affect each?

<u>Test 2</u>

<u>Section A</u>

1. Discuss the purpose of the core in the transformer. Why was the secondary voltage so small when one of the coils was removed from the core?
2. (<u>a</u>) Would a transformer operate in a DC circuit? Discuss.

(b) How would the output voltage of a transformer change if the number of turns in the secondary were doubled? Discuss why in terms of magnetic flux and induced voltages.

3. Describe the construction of a capacitor. Can a DC current flow through it? Why or why not? How can an AC current "flow" through it? How can it be used to store energy?

4. How would the current through an inductor placed across 10 V DC compare with that when it is placed across 10 V AC? Why do these currents differ? What factors in the construction of an inductor can be used to increase its inductance?

Section B

5. Discuss why the sum of the rms voltages across the elements of a series AC circuit containing inductance and capacitance is larger than the applied voltage. How is the instantaneous current in the inductor related to that in the capacitor at the same time?

6. Given two capacitors, $C_1 = 5\ \mu F$ and $C_2 = 10\ \mu F$, what is the effective capacitance when they are connected in parallel? In series? What is the net inductance of two .3-H inductors connected in series?

7. How does inductive reactance change as the frequency is doubled? Halved? Show why. How does capacitive reactance change as the frequency is doubled? Halved? Show why.

8. Distinguish among paramagnetic, diamagnetic, and ferromagnetic materials. Discuss briefly atomic behavior which could account for the observed properties of each kind of material.

Section C

9. An engineer wants a circuit to resonate at 10,000 Hz. If an inductor of .01 H is available, what capacitance must be used?

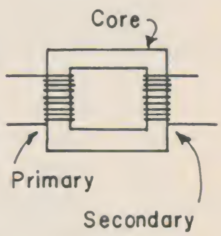
10. Use the definition for the efficiency of a transformer to show that for a step-up transformer, the secondary current must be less than the primary current; and that for a step-down transformer, the secondary current should be greater than the primary current. You may assume the transformer is ideal.

11. A voltage of 128 V is applied to the primary of a doorbell transformer. If the transformer has 1600 turns in the primary and 200 turns in the secondary, what will be the secondary voltage? Will the full secondary voltage you calculated be measured in real life? Why?

12. (a) Why does no one make transformers with solid iron cores? Discuss.
(b) How could a given transformer be redesigned to reduce copper losses? Discuss.

Answers to Post-Tests

Test 1



1. If the secondary has more turns than the primary, the voltage will be stepped up by a factor N_2/N_1 times the input voltage. If the secondary has fewer turns than the primary, the voltage will be stepped down by the same factor of N_2/N_1 times the input voltage.

2. Scope set for .5 V/cm; $V_{peak} = 1$ V, $V_{rms} = V_{peak}/\sqrt{2} = 1/\sqrt{2} = .7\ V_{rms}$.

3. Reluctance of a material is a measure of the resistance of the material to the presence of magnetic field lines. Flux will decrease with increasing reluctance, and vice versa. Reluctance can be increased by decreasing the

permeability, increasing the length of the ring, or (as discussed on p. 48 in Sec. C) decreasing the cross-sectional area. $\mathcal{R} = \ell/\mu A$.

4. 1500 turns; 150,000 turns
5. Capacitive reactance is the effective AC impedance of the capacitor; $\underline{V}_C/\underline{I}_C = \underline{X}_C$, similar to the DC case $\underline{V}_R/\underline{I}_R = \underline{R}$.
$\underline{X}_C = 1/2\pi \underline{f}\underline{C}$
$\underline{I}_C = \underline{V}_C/\underline{X}_C$
6. $\underline{I} = \underline{V}/\underline{X}_L = \underline{V}/2\pi\underline{f}\underline{L} = 62.8/(2\pi 60)(.5)$
$= .33\ A_{rms}$
7. See page 33.
8. Cos 30° = .87
$\underline{P} = (3)\ (100)\ (.87) = 261$ watts
9. $\underline{f}_R = 1/2\pi\sqrt{LC}$
If $\underline{C}$ is doubled, $\underline{f}$ is reduced by $1/\sqrt{2}$.
If $\underline{L}$ is quadrupled, $\underline{f}$ is reduced by 1/2. $\underline{f}_R$ is unaffected by a voltage change.
10. From Experiment A-2, we found that the sum of the voltages across the elements in an AC circuit will usually add to more than the input voltage because the voltages are out of phase with each other. This tells us that the effective impedance of the whole circuit is less than the sum of the separate impedances: $\underline{V}_{in} < \underline{V}_L + \underline{V}_R + \underline{V}_C$
$\underline{V}_{in}/\underline{I} < \underline{V}_L/\underline{I} + \underline{V}_R/\underline{I} + \underline{V}_C/\underline{I}$
$\underline{X}_{eff} < \underline{X}_L + \underline{R} + \underline{X}_C$
The smaller effective impedance will allow a larger current to flow. Energy dissipated = VI cos ϕ. For pure capacitor and pure inductor, $\underline{V}$ and $\underline{I}$ are 90° out of phase, cos 90° = 0, so no energy dissipated. For the resistor, $\underline{V}$ and $\underline{I}$ must be in phase, Power = $\underline{VI}$.
11. The efficiency is the output power divided by the input power times 100. Efficiency can never be more than 100%, as you can't get out more than you put in. Actually, no real transformer can even be 100% efficient because of losses. The copper and eddy-current losses increase with higher power output, so the efficiency drops. Hysteresis losses do not increase as rapidly as these resistive heating losses.
12. (a) Eddy-current losses: currents induced in the core material (any conductor) dissipate energy by resistive heating of the core due to the currents. Minimize by use of laminated core to reduce the eddy-current formation. Larger currents cause larger induced eddy currents and more losses.
(b) Hysteresis losses: energy is required to change the directions of the magnetic moments of the core atoms every time the magnetic field reverses. Minimize by use of core materials that waste less energy in this magnetization-demagnetization process, i.e., transformer iron. Larger currents cause greater magnetization and greater losses, although these losses do not increase as rapidly with current as the other two main losses.
(c) Copper losses: Any nonzero resistance will have a power loss $\underline{P} = \underline{V}\ \underline{I}$ cos 0°. Because the coils have resistance, they have losses. Minimize by use of low-resistance wires. $\underline{P} = \underline{VI} = (\underline{IR})\ \underline{I} = \underline{I}^2\underline{R}$. Power loss increases as square of current.

Test 2

1. A core serves to concentrate magnetic field lines so that the primary and secondary are flux-linked by the field as closely as possible. Aluminum and wood are not ferromagnetic, so they do not form a "magnetic circuit" when used as a core (their reluctance is about the same as air, and is much larger than iron.); without the iron there is only a fraction of the magnetic flux linkage that the

iron provided, if any at all.

2. (a) A transformer would not operate on DC. Transformer operation depends on currents being induced in the secondary by a changing magnetic field (Faraday's Law).

(b) Double turns in secondary, double output voltage. Same flux through each turn, so each turn has same induced voltage, in series with all the others; if one adds N more turns, secondary voltage increases by N x voltage induced per turn.

3. Capacitor formed by two conductors placed close to each other, but insulated from each other. No DC current can flow because no conducting path is present. AC can "flow" through it by charging, discharging, and recharging the capacitor with opposite polarity many times per second. Whenever the capacitor has a voltage across it and charges of opposite sign on the plates, the energy to charge the plates is stored in it, and can be released by shorting the plates with a wire.

4. Much larger current with DC source. DC impedance of inductor is just the resistance R of the copper wire; $X_L = R + 2\pi f X_L$. Inductance can be increased by using iron core to maximize flux linkage and using large numbers of turns.

5. Instantaneous voltages across each of the elements in the series circuit must add to the input voltage. Because the voltages across the elements are not in phase, the maximum voltages across each of the elements can add to a larger value than V_{in} (since the maxima are not all reached at the same time). Instantaneous current is the same in all elements at each instant.

6. parallel $C = C_1 + C_2 = 15\ \mu F$

series $\frac{1}{C} = \frac{1}{C_1} + \frac{1}{C_2} = 3.3\ \mu F$

series $L = L_1 + L_2 = .6$ H

7. $X_L = 2\pi f L$; f doubled, X_L doubled; f halved, X_L halved.
$X_C = 1/2\pi f C$; f doubled, X_C halved; f halved, X_C doubled.

8. See page 12 ff, page 35 ff.

9. $f = 1/2\pi\sqrt{LC}$, $C = 1/4\pi^2 L f^2 = 0.025\ \mu F$.

10. Efficiency = (Power out/Power in) x 100. Since efficiencies must be at most 100% or less: power out $\leq$ power in. $V_2 I_2 \leq V_1 I_1$, so that for an ideal transformer: $V_1/V_2 = I_2/I_1$. Therefore, for step-up ($V_2 \geq V_1$), $I_1 > I_2$, and for step-down ($V_2 < V_1$), $I_1 < I_2$.

11. $V_2 = N_2/N_1 \cdot V_1 = \frac{200}{1600} \times 128 = 16\ V_{rms}$. Losses will reduce this in real life.

12. (a) Solid core transformers would have much larger eddy-current losses.

(b) Copper losses could be reduced by reducing the resistance of the wire in the winding, i.e., use larger wires. But these would cost a lot more to produce.

IX LIST OF APPARATUS

1. Demountable transformer illustrated in Exp. A-1 of the student module that is available from Thornton Associates. Should have two primary windings and two or three secondary. Core is U-I type, with clamping device. Laminated and solid iron cores, aluminum and wood core.

2. Low-voltage (30 V AC, ½ A) power supply isolated from ground, such as Thornton Associates' VPS-300; or combination of variable transformer and isolation transformer; or normal audio-frequency sine-wave generator (required for optional experiments) such as Thornton Associates' FGR-100. If you use a signal generator,

slightly more sensitive scopes and meters are required than otherwise.

3. Various inductors in range from fractions of henries to several henries (if filter chokes are used, note that the value of the inductance may vary with the current, and hence may not agree with the labelled value). Useful values: 1H, 5H, .1H.
4. Various capacitors in range from .1 μF to several μF. Useful values: 1 μF, 2 μF, 5 μF.
5. Various resistors in range from 10 Ω through 10 kΩ. Light bulbs described in Section VI may be used. Most useful value: 100 Ω, 2 watt.
6. Two multirange AC voltmeters (approx. range: .1 V full scale to 10 or 15 Vfs). Two AC ammeters (approx. range: .1 A fs to 3 A fs).
7. 3 x 5 file cards for shims.
8. Cathode Ray Oscilloscope, dual-trace such as Thornton Associates' 4D-10, or single-trace scope with Heath Kit ID-101 Electronic switch. (See discussion in Sec. V.)

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